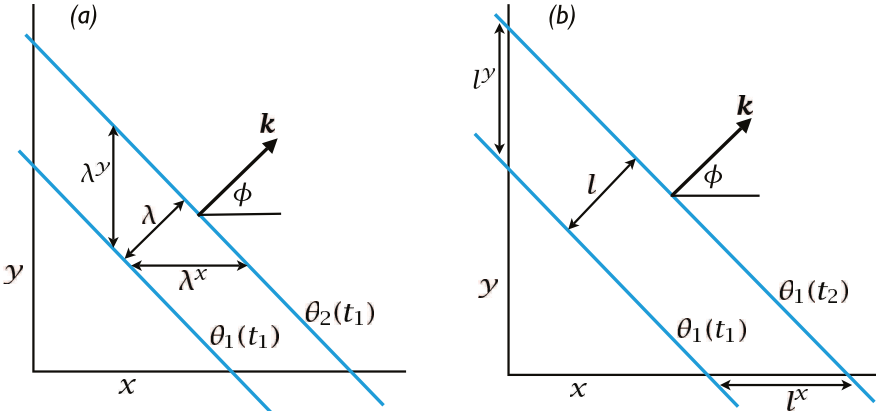

(a)
k
λ^y
λ
ϕ
λ^x
y
$\theta_2(t_1)$
$\theta_1(t_1)$
x
(b)
l^y
k
l
ϕ
y
$\theta_1(t_2)$
$\theta_1(t_1)$
x
l^x

Fig. 6.1

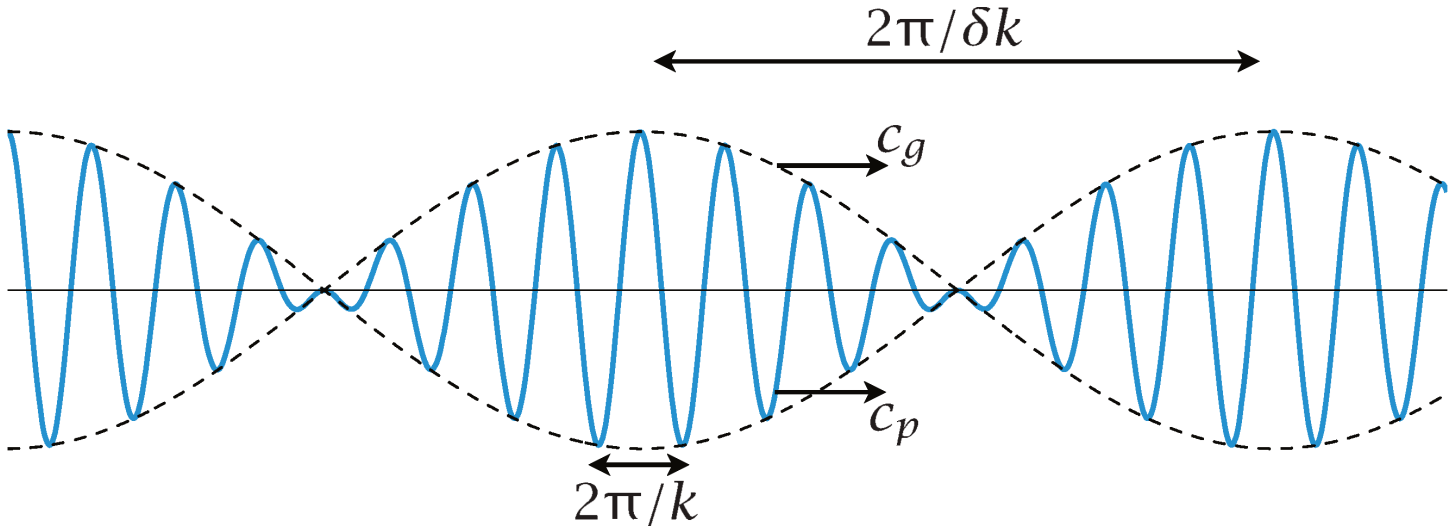


Fig. 6.2

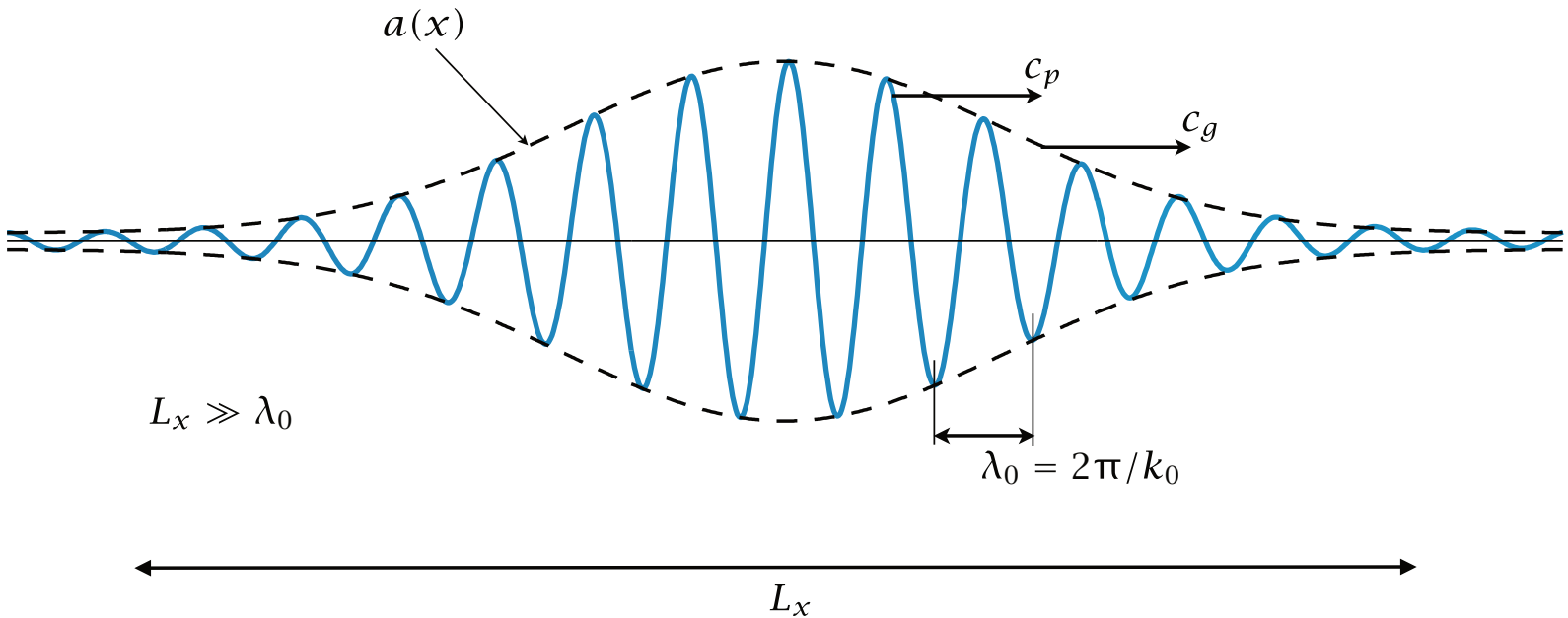


Fig. 6.3

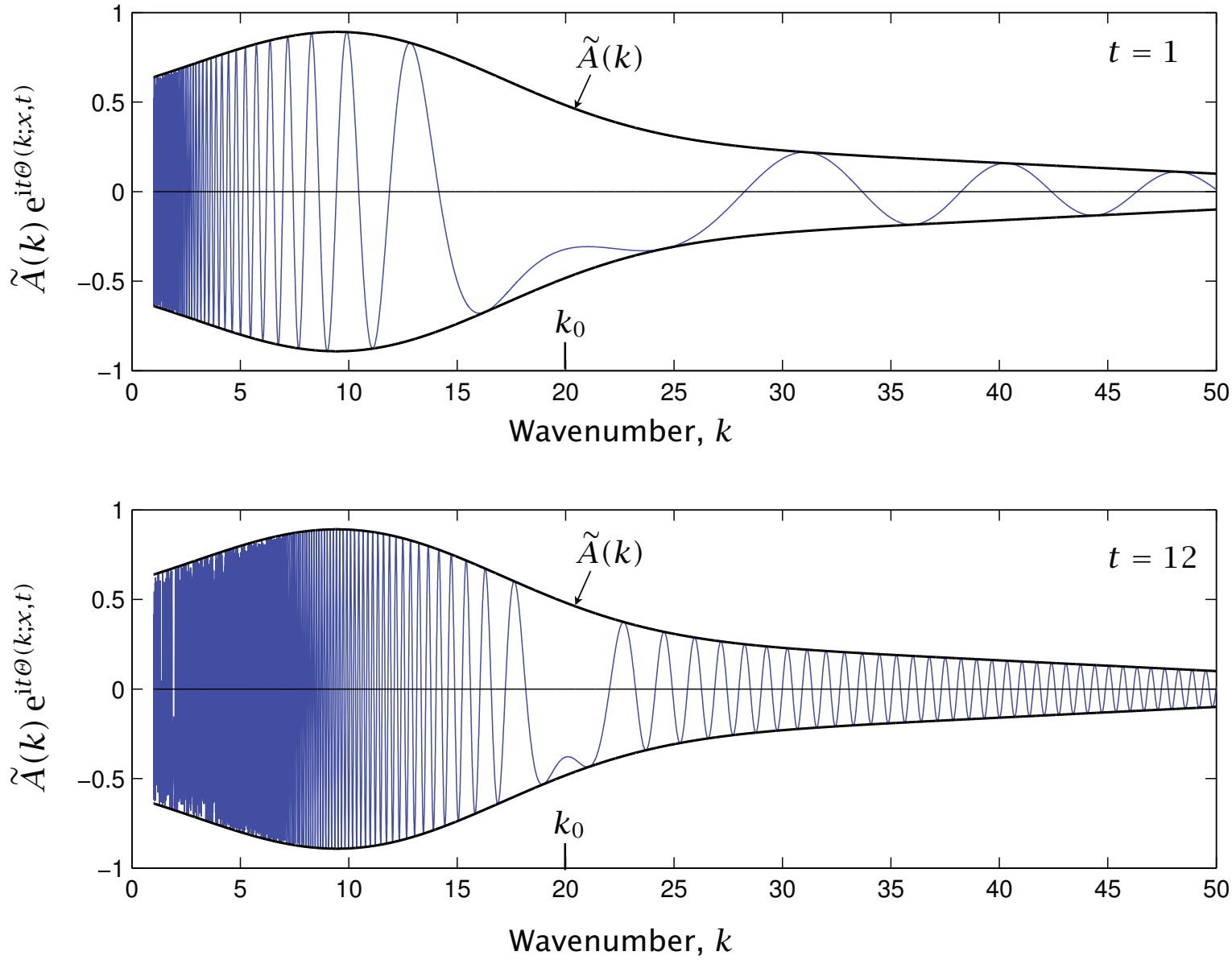

$\tilde{A}(k)\, e^{it\Theta(k;x,t)}$
$\tilde{A}(k)$
$t = 1$
k_0
Wavenumber, k
$\tilde{A}(k)\, e^{it\Theta(k;x,t)}$
$\tilde{A}(k)$
$t = 12$
k_0
Wavenumber, k

Fig. 6.4

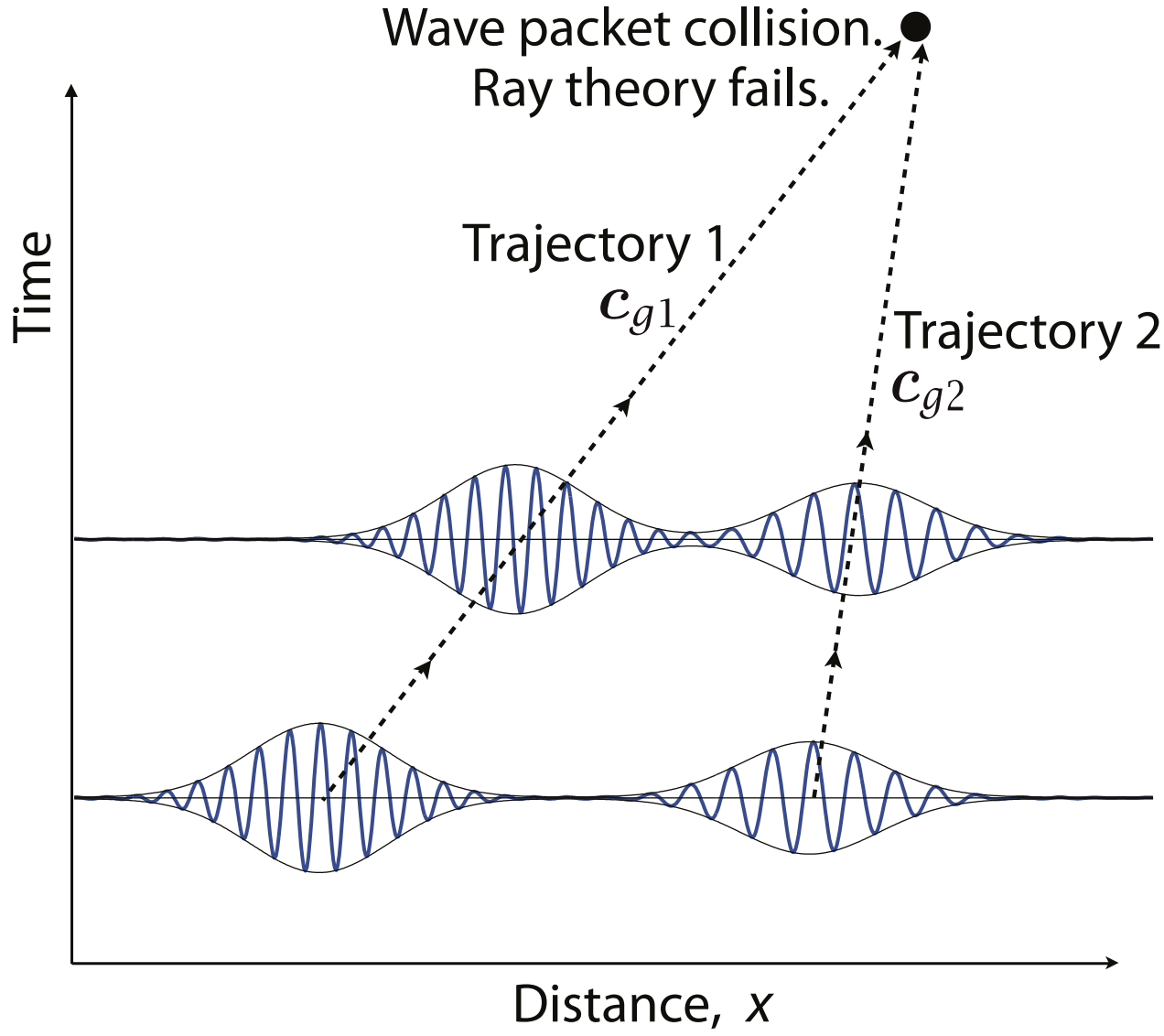

Wave packet collision.
Ray theory fails.
Trajectory 1
c_{g1}
Trajectory 2
c_{g2}
Time
Distance, x

Fig. 6.5

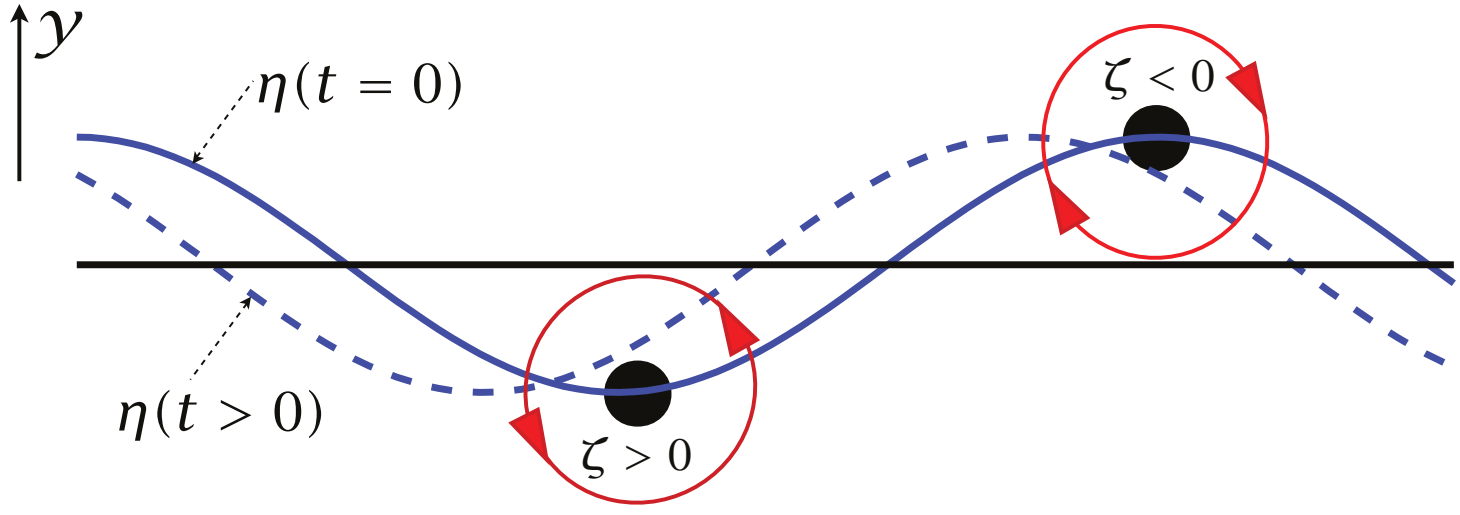
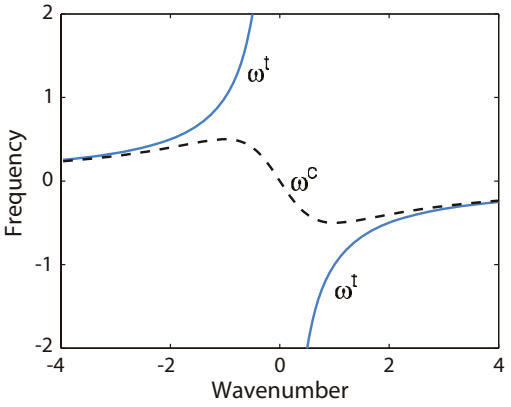


Fig. 6.6


Frequency
Wavenumber
ω^t
ω^c
ω^t
2
1
0
-1
-2
-4
-2
0
2
4

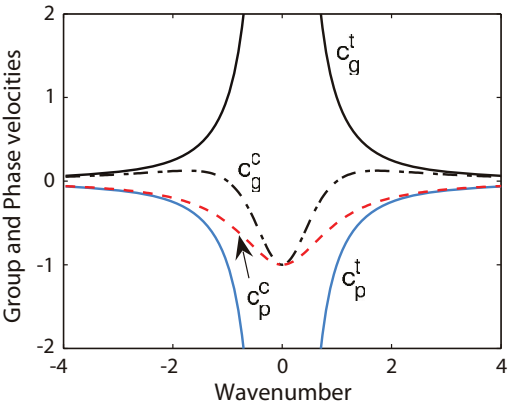

Group and Phase velocities
Wavenumber
c_g^t
c_g^c
c_p^c
c_p^t
2
1
0
-1
-2
-4
-2
0
2
4

Fig. 6.7

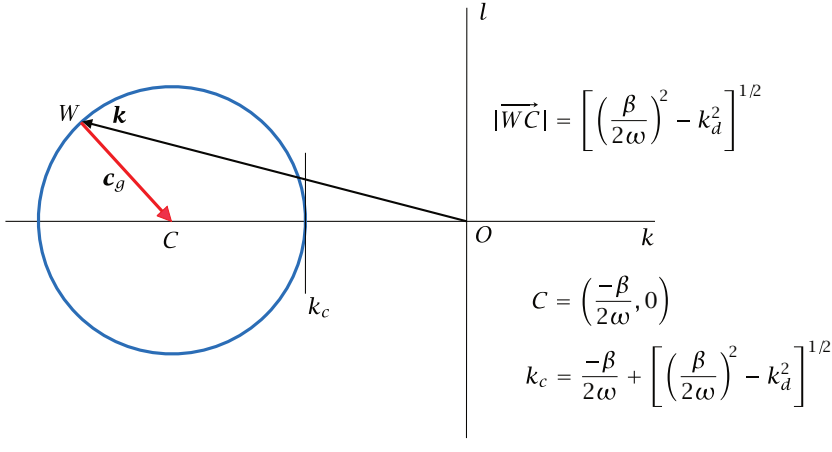

l
W
k
c_g
C
O
k
k_c
$|\overrightarrow{WC}| = \left[\left(\frac{\beta}{2\omega}\right)^2 - k_d^2\right]^{1/2}$
$C = \left(\frac{-\beta}{2\omega}, 0\right)$
$k_c = \frac{-\beta}{2\omega} + \left[\left(\frac{\beta}{2\omega}\right)^2 - k_d^2\right]^{1/2}$

Fig. 6.8

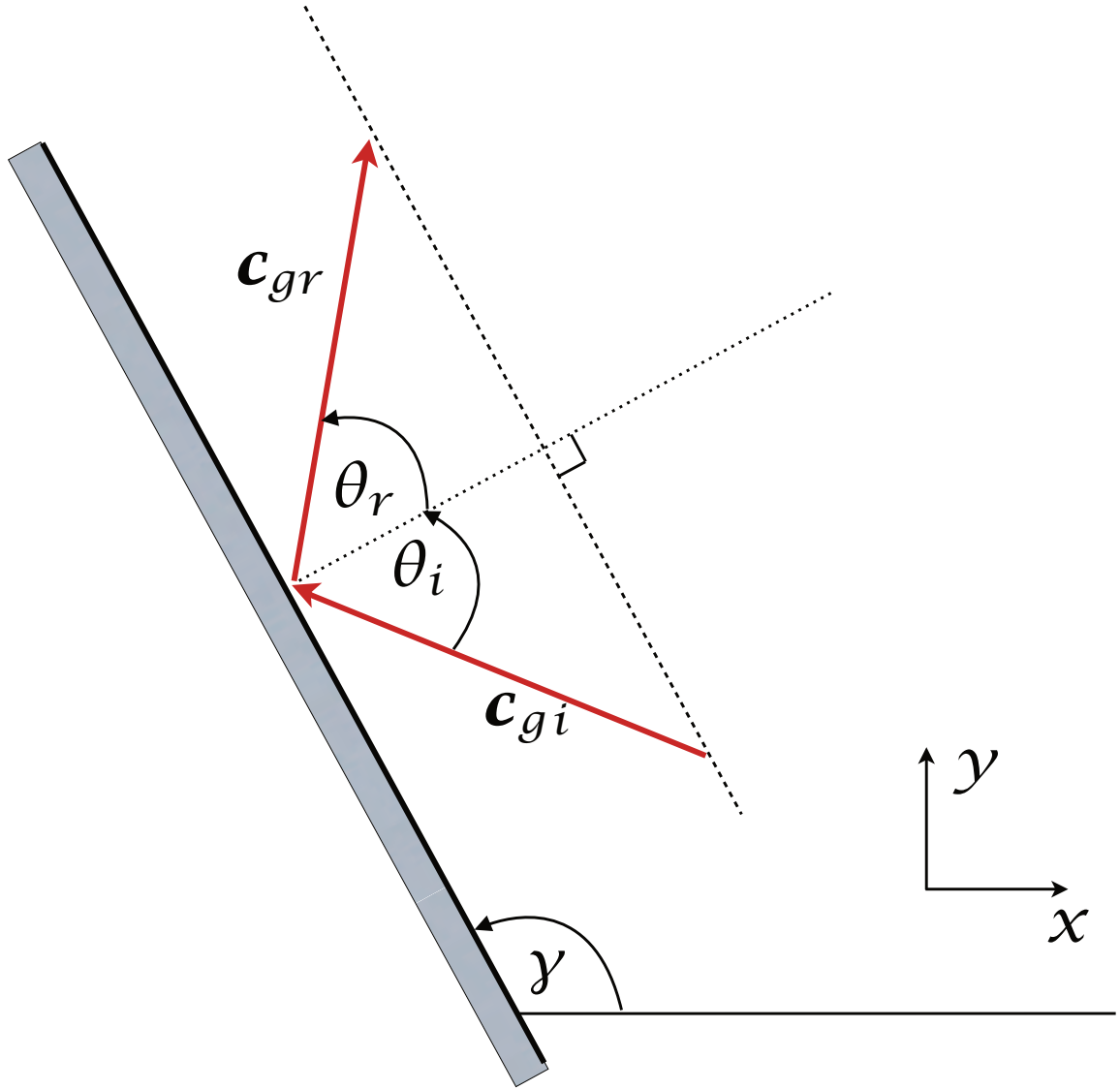


Fig. 6.9

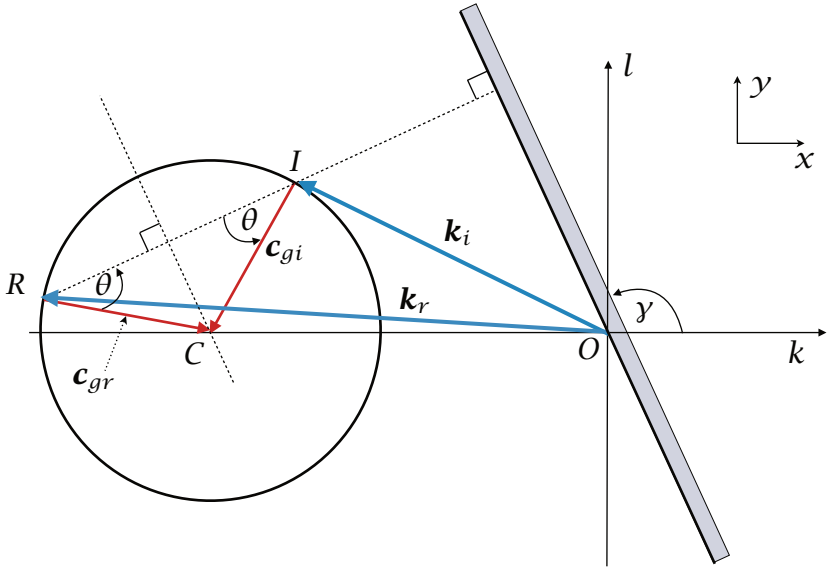


Fig. 6.10

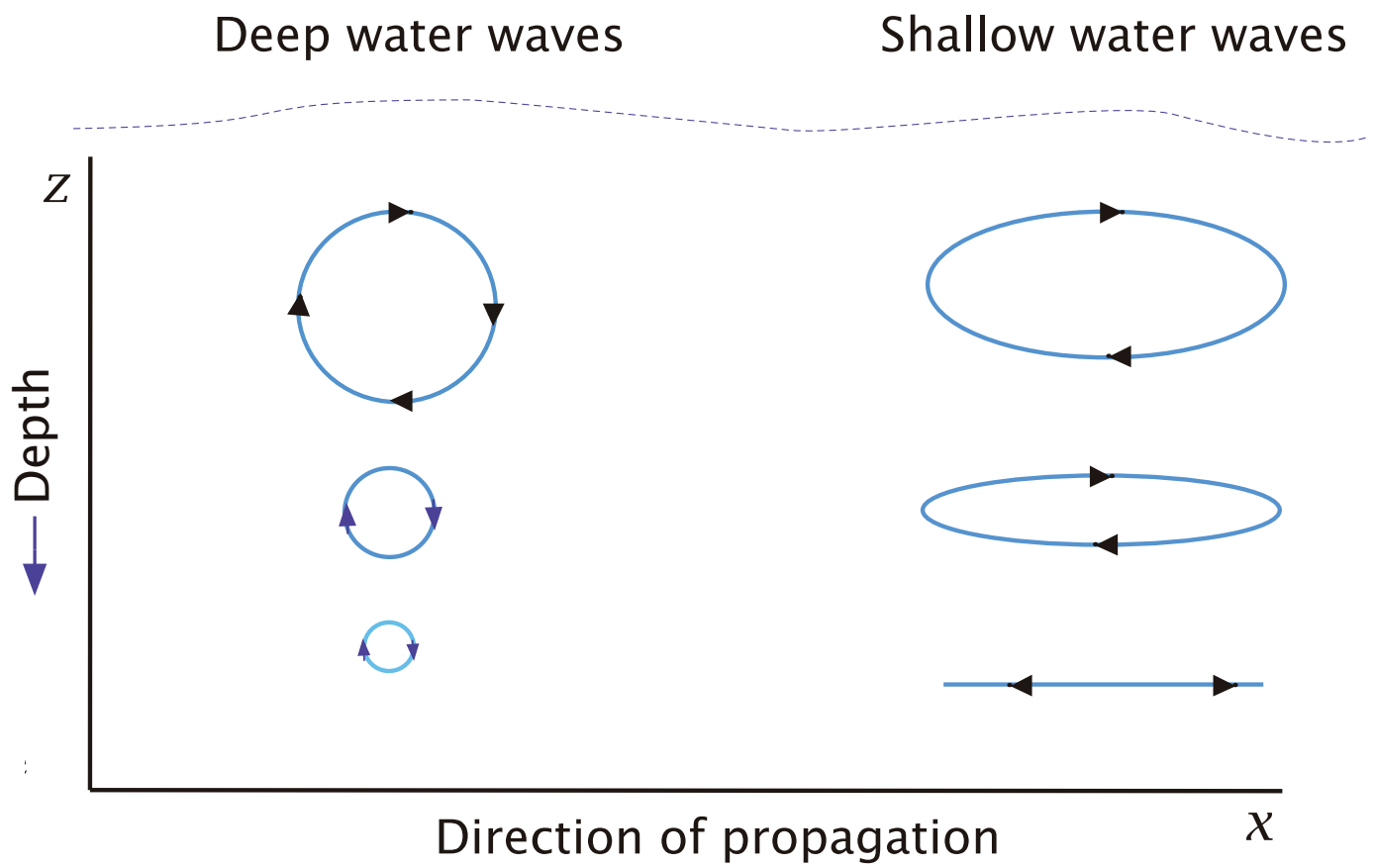

Deep water waves
Shallow water waves
z
Depth
Direction of propagation
x

Fig. 7.1

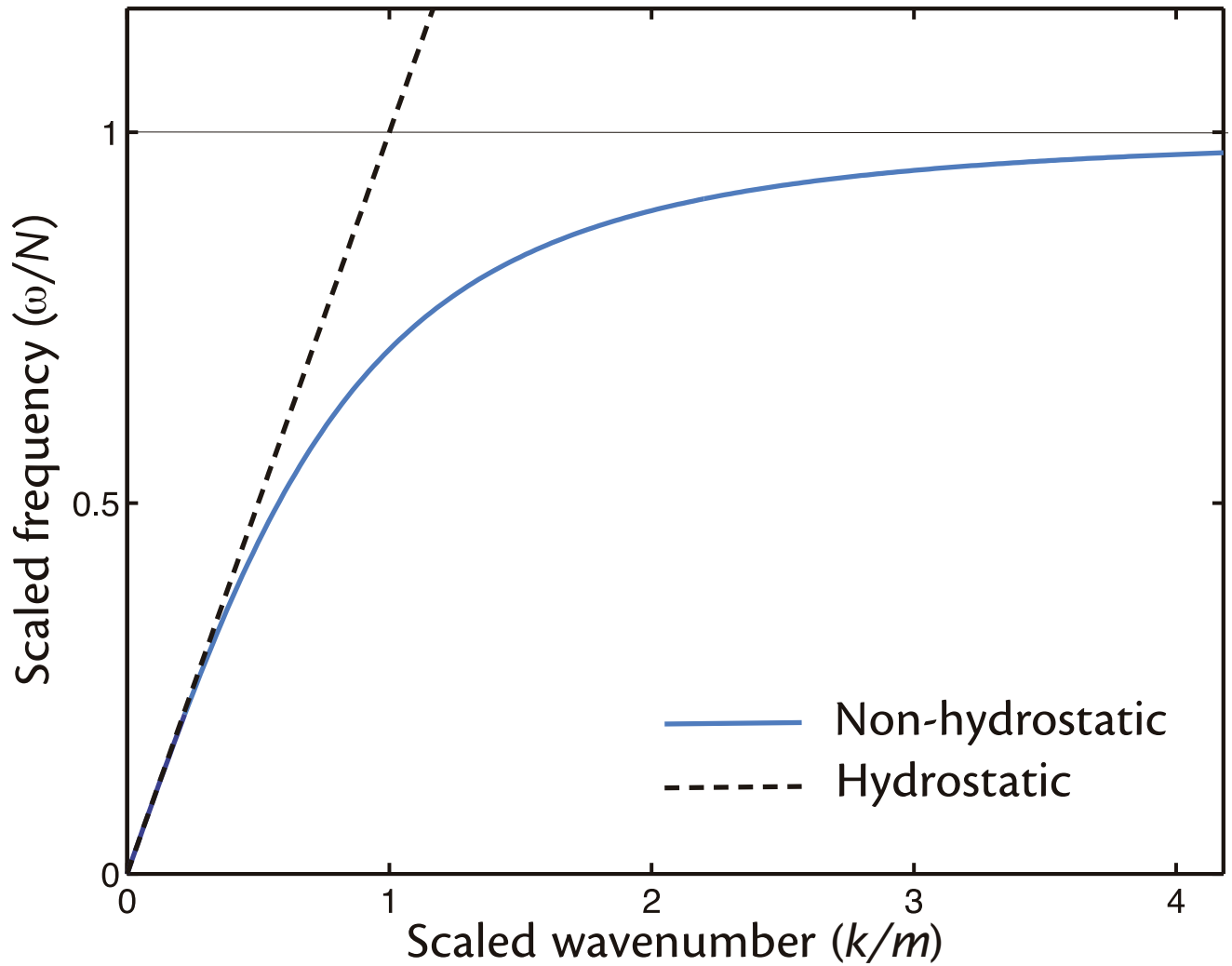

Scaled frequency (ω/N)
1
0.5
0
0
1
2
3
4
Scaled wavenumber (k/m)
Non-hydrostatic
Hydrostatic

Fig. 7.2

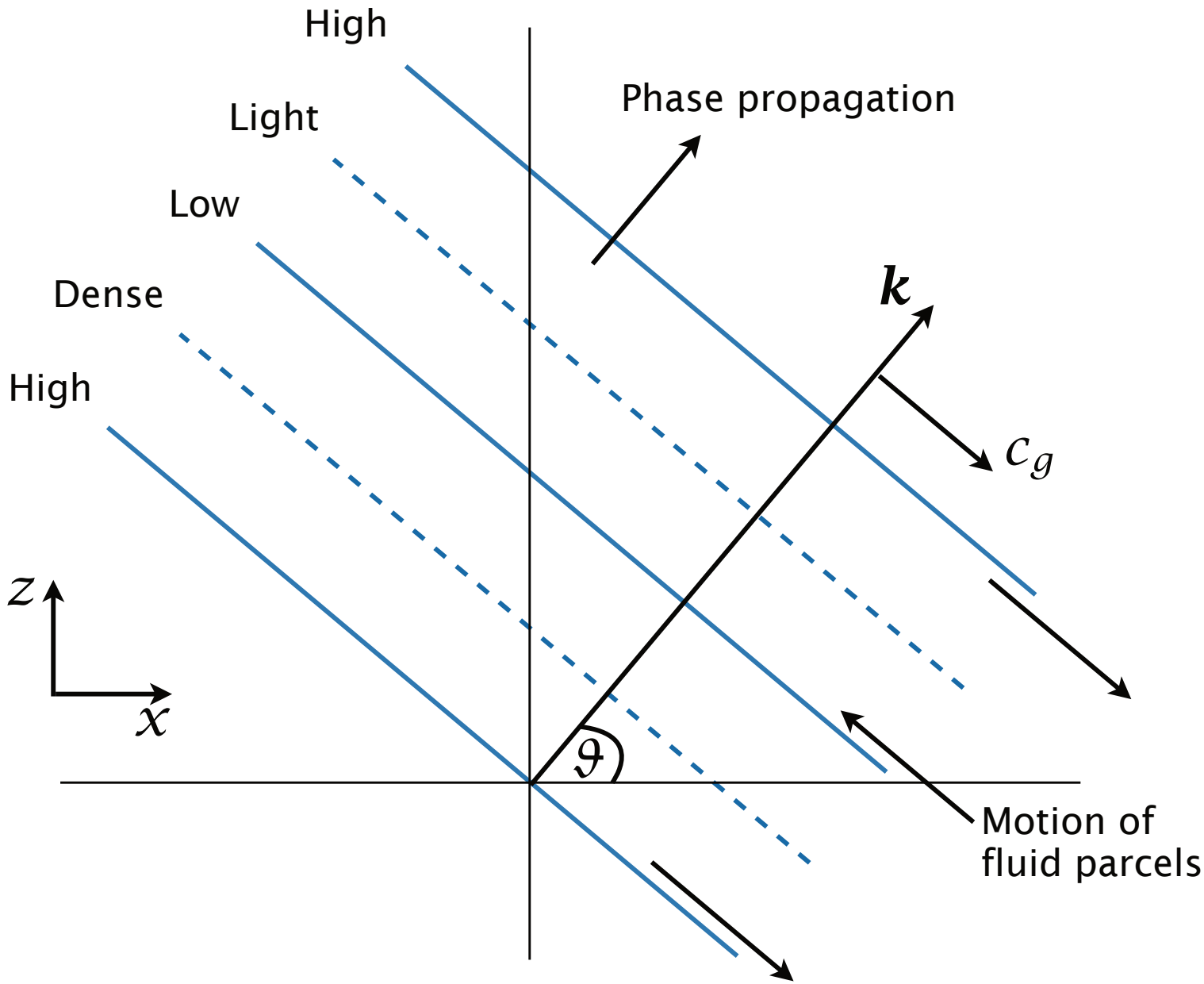

High
Light
Low
Dense
High
Phase propagation
k
c_g
z
x
ϑ
Motion of
fluid parcels

Fig. 7.3

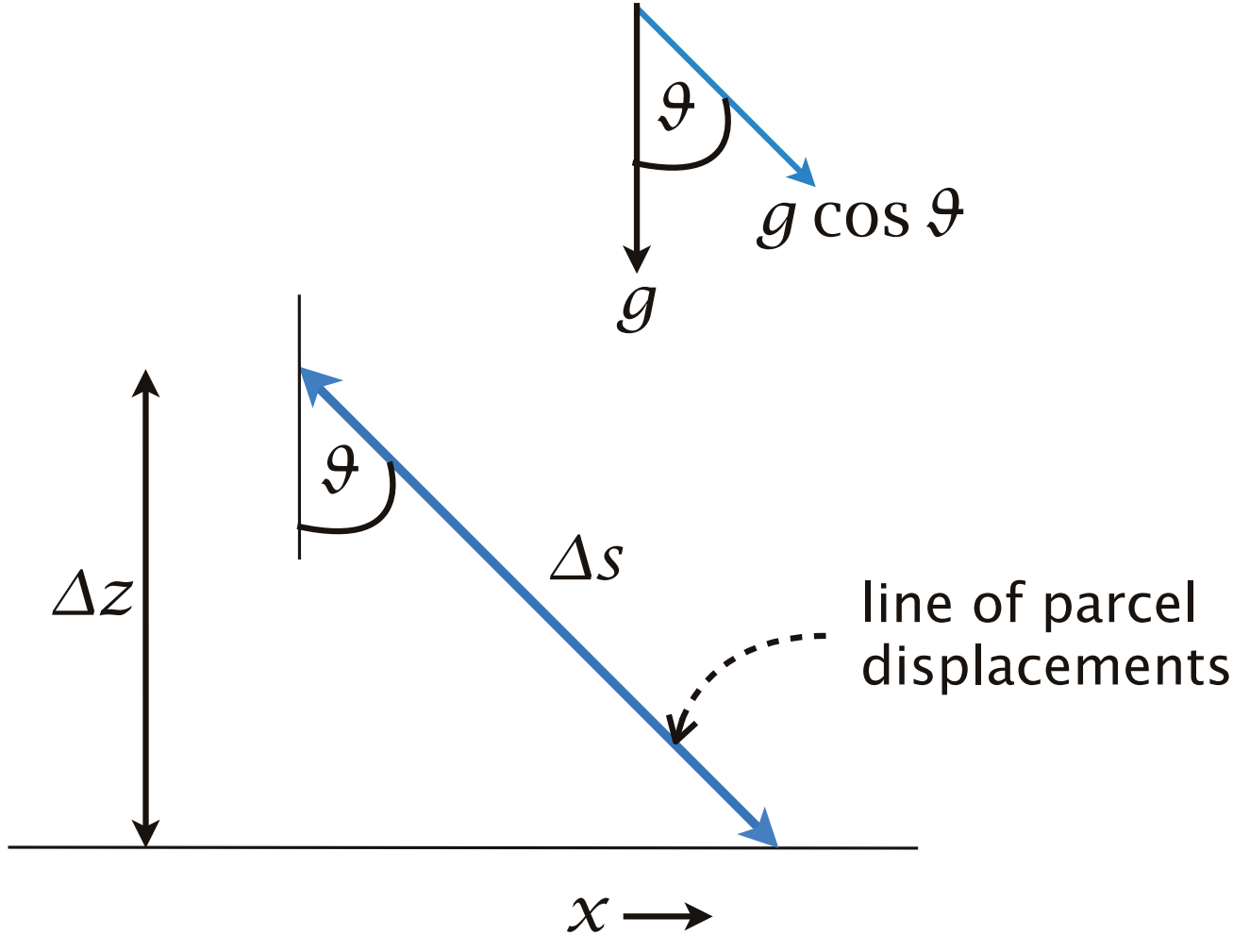


Fig. 7.4

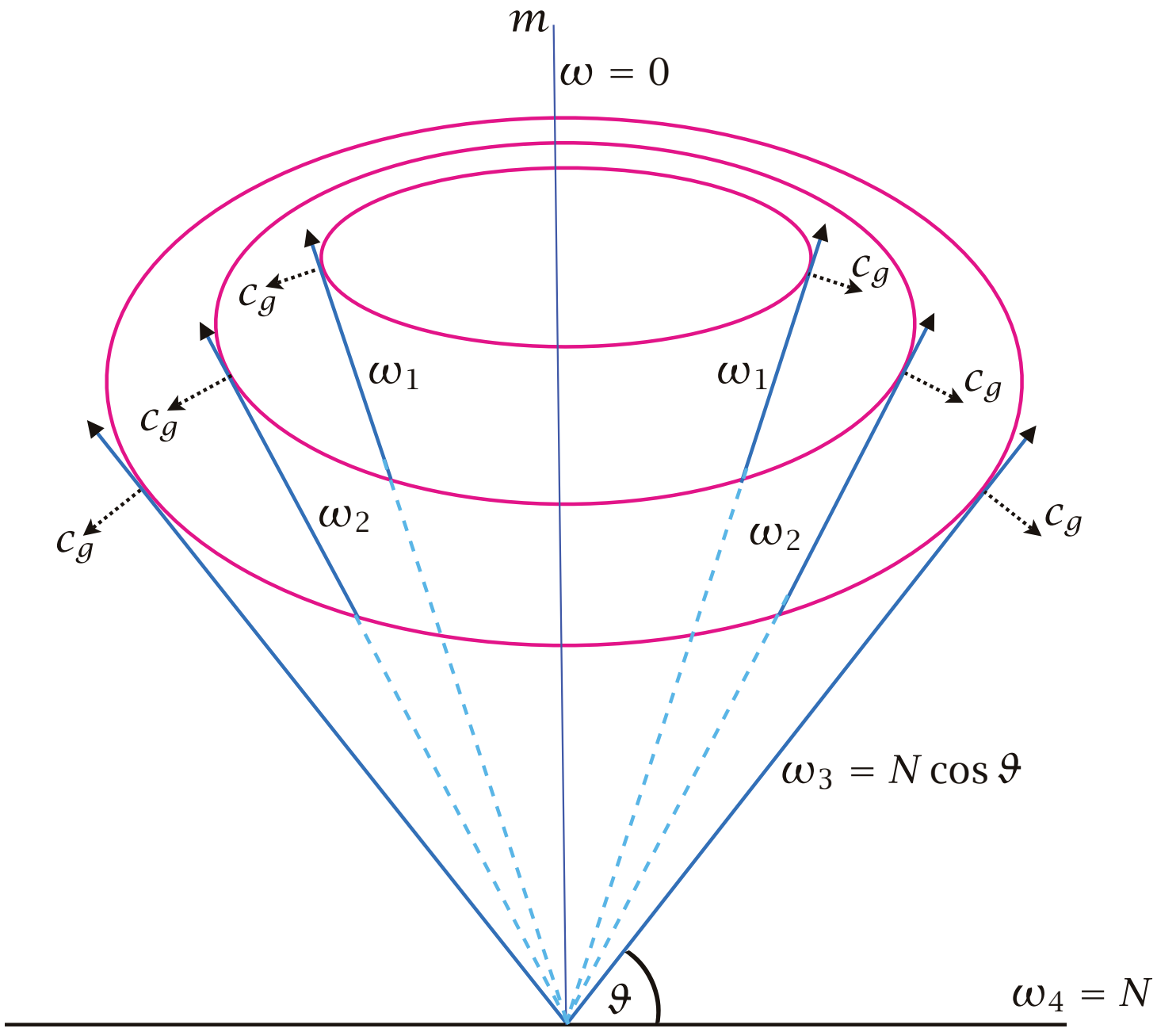


Fig. 7.5

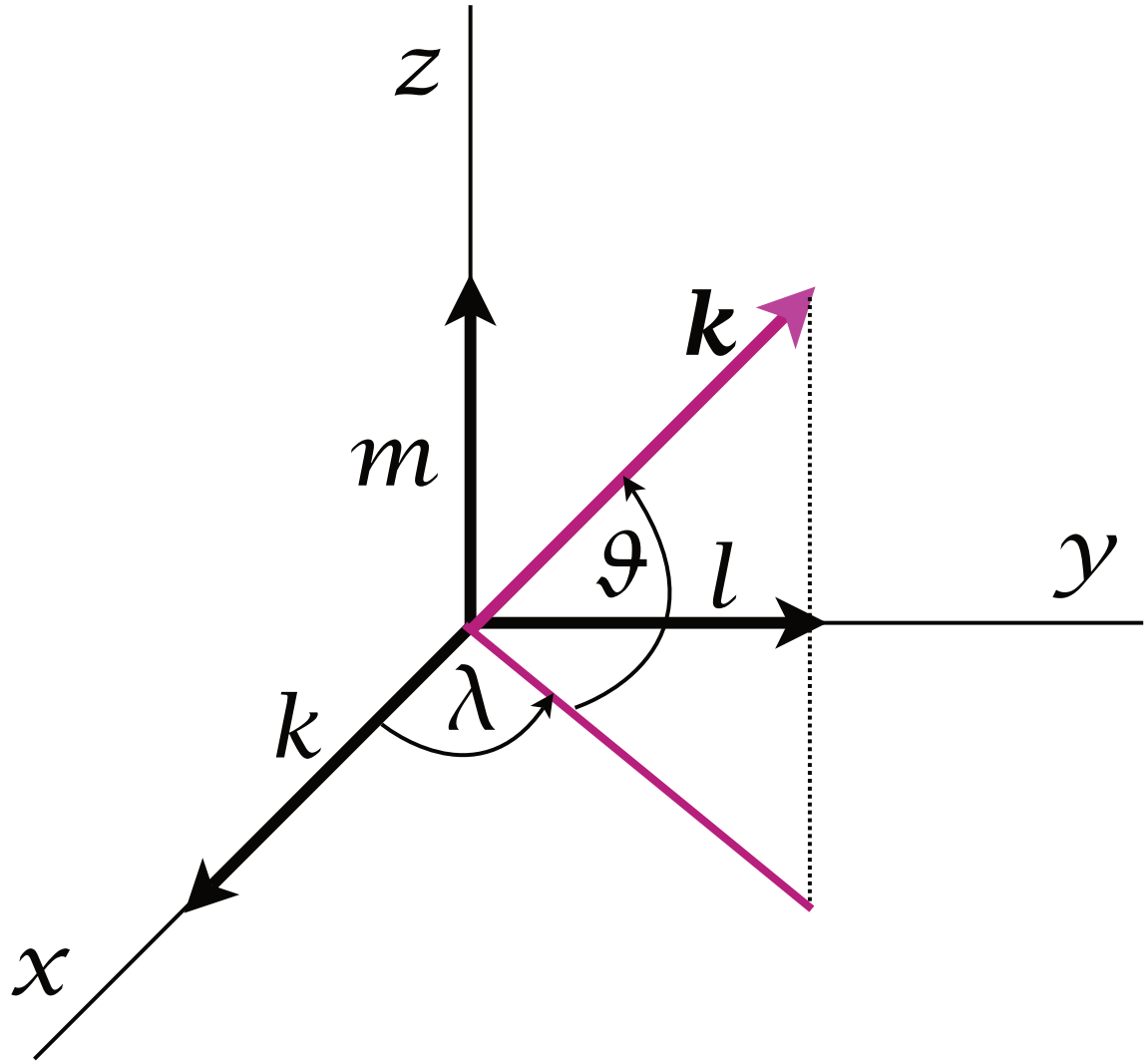


Fig. 7.6

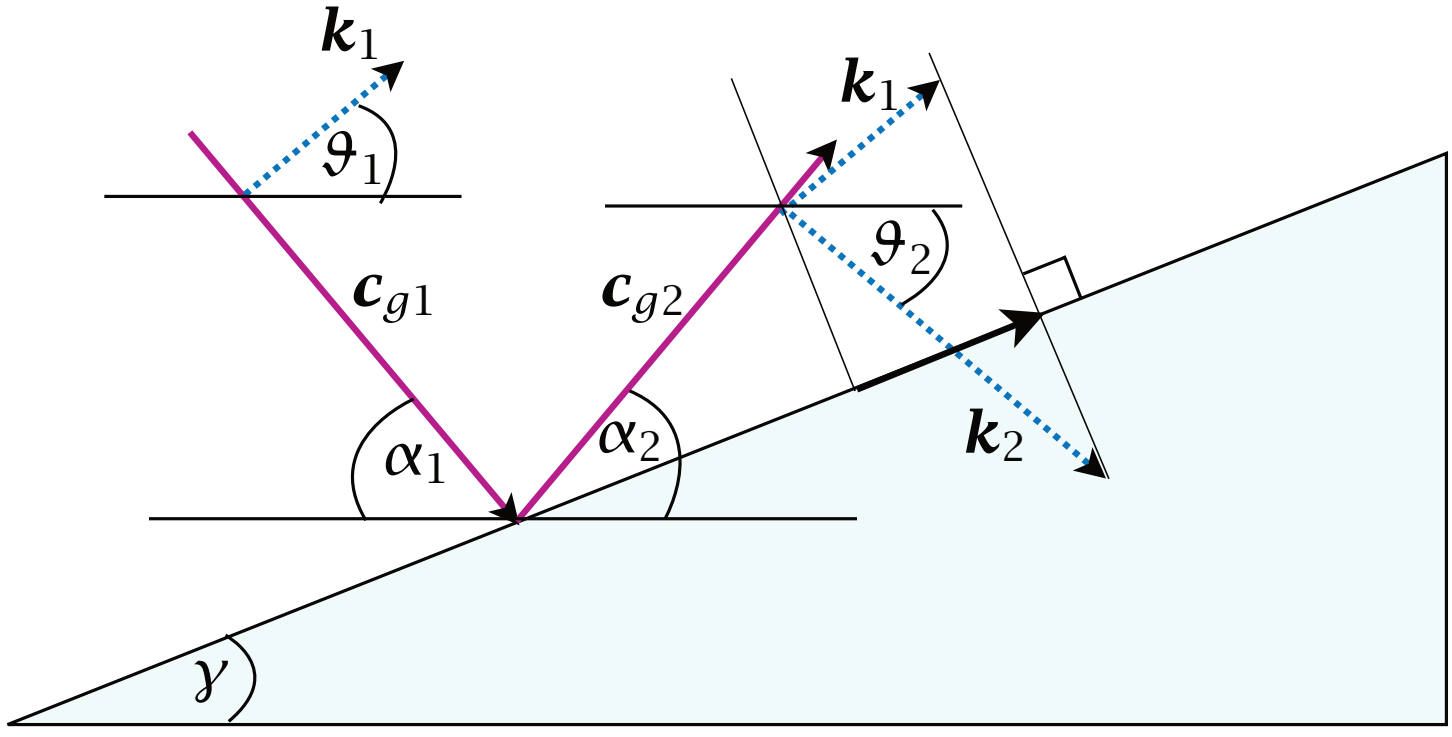

$\boldsymbol{k}_1$
ϑ_1
$\boldsymbol{c}_{g1}$
α_1
$\boldsymbol{k}_1$
ϑ_2
$\boldsymbol{c}_{g2}$
α_2
$\boldsymbol{k}_2$
γ

Fig. 7.7

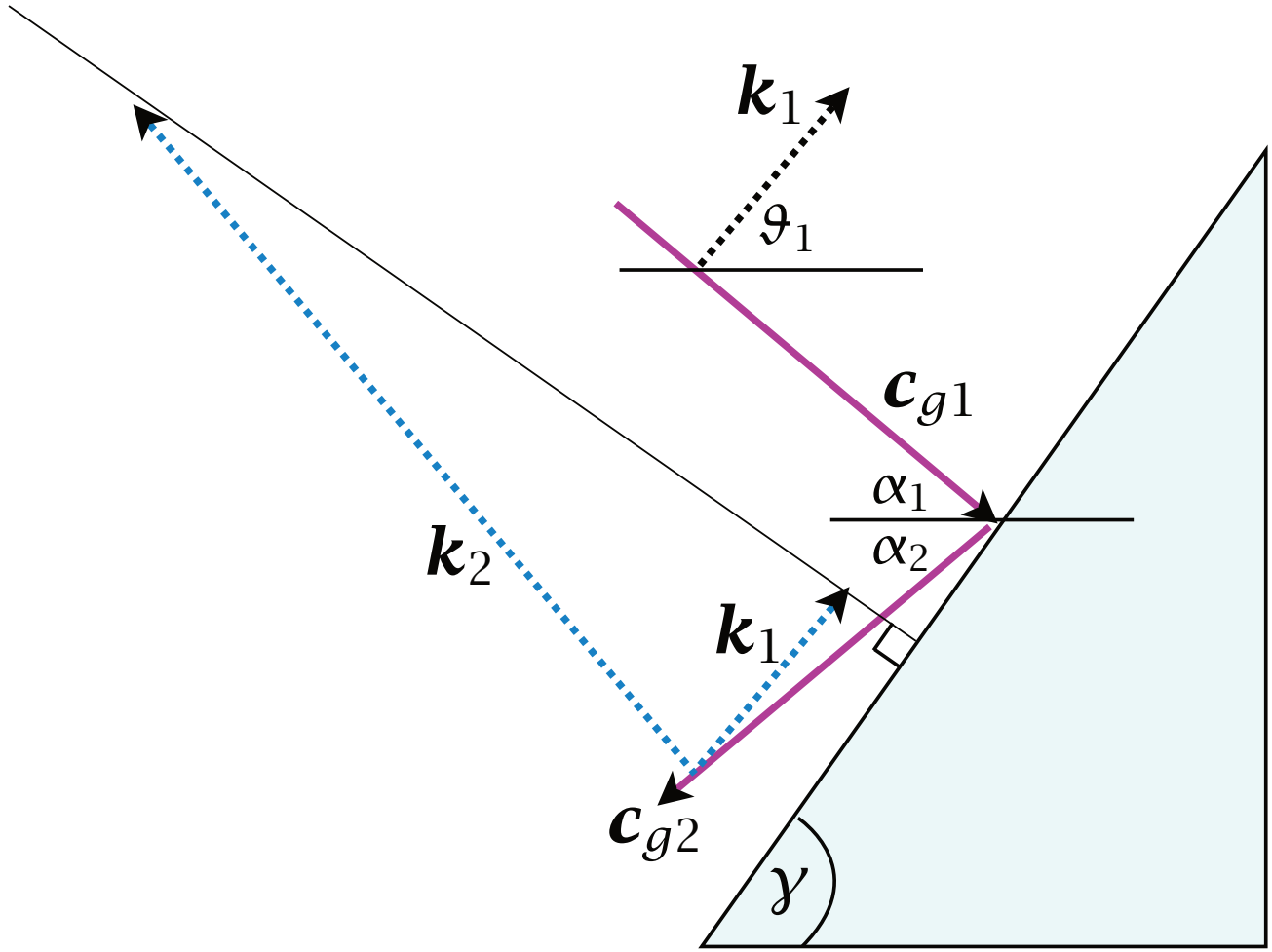

$\boldsymbol{k}_1$
ϑ_1
$\boldsymbol{c}_{g1}$
α_1
α_2
$\boldsymbol{k}_2$
$\boldsymbol{k}_1$
$\boldsymbol{c}_{g2}$
γ

Fig. 7.8

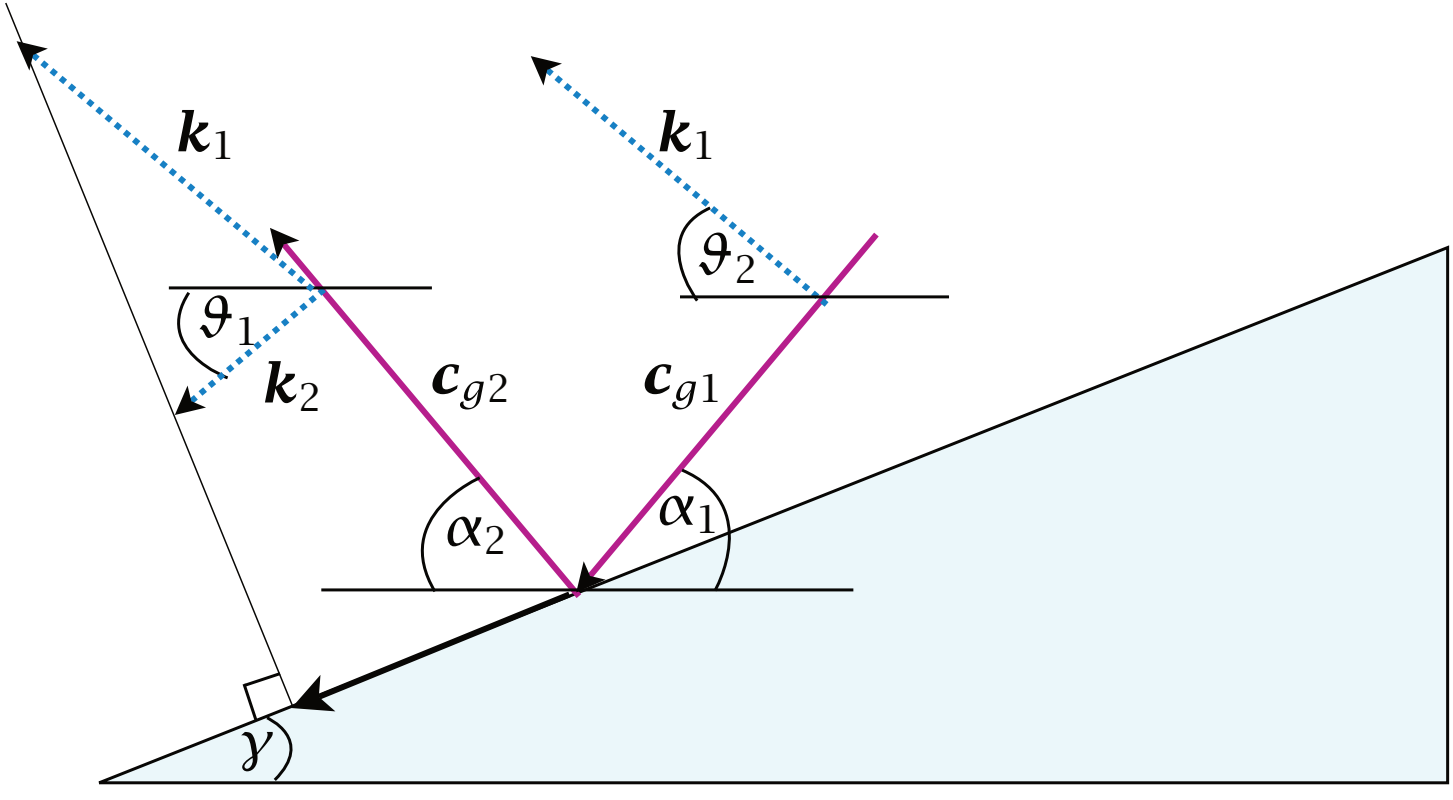


Fig. 7.9

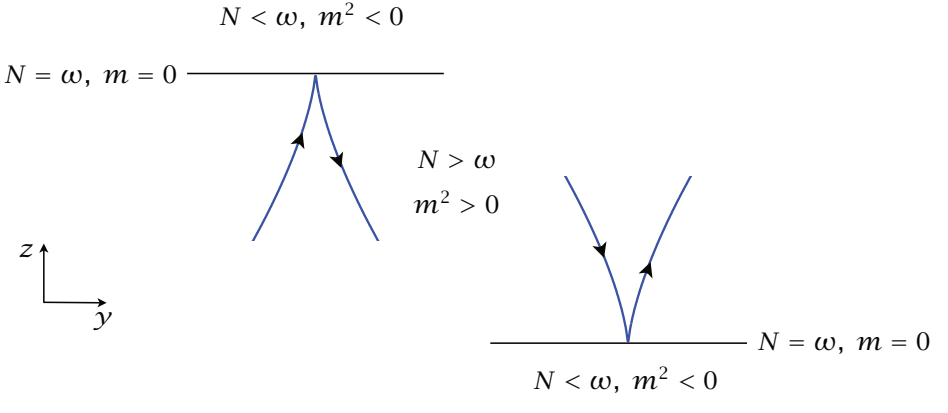


Fig. 7.10

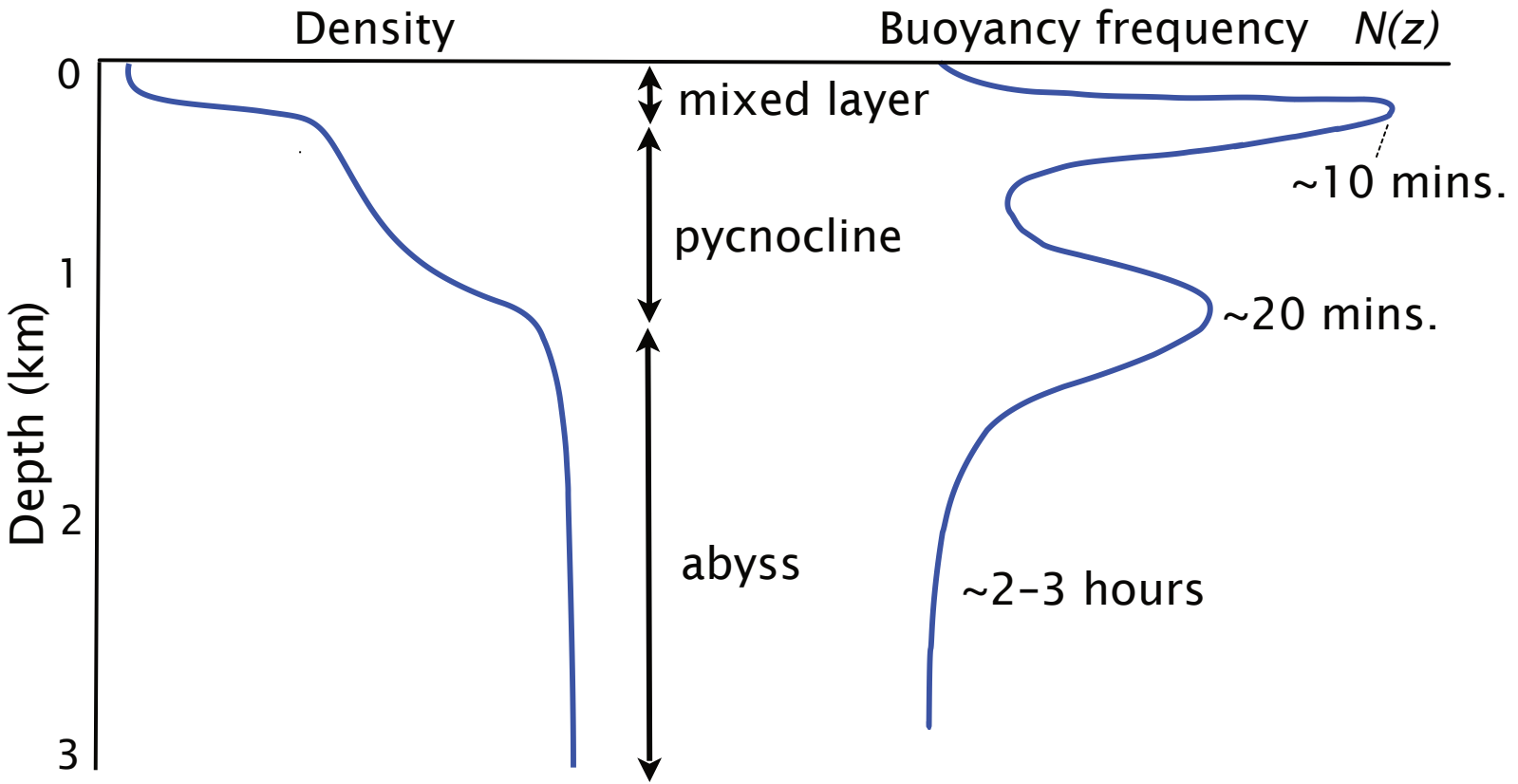
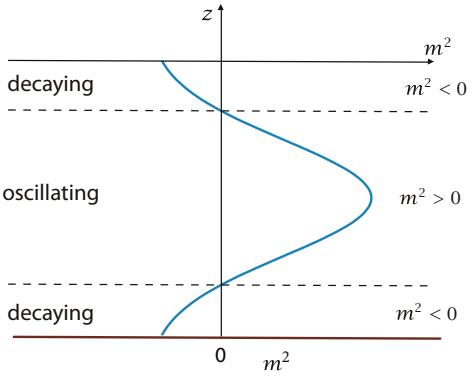

Density
Buoyancy frequency N(z)
0
1
2
3
Depth (km)
mixed layer
pycnocline
abyss
~10 mins.
~20 mins.
~2–3 hours

Fig. 7.11


z
m²
decaying
m² < 0
oscillating
m² > 0
decaying
m² < 0
0
m²

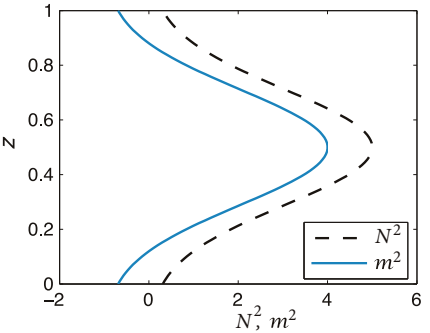
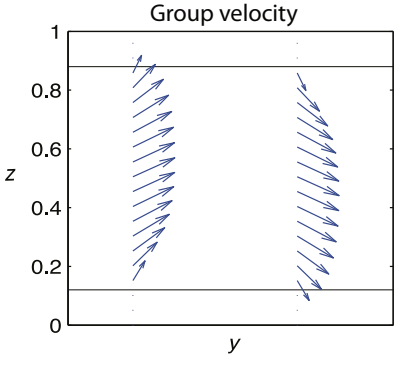

1
0.8
0.6
0.4
0.2
0
z
−2
0
2
4
6
N², m²
N²
m²

Fig. 7.12


Group velocity
1
0.8
0.6
0.4
0.2
0
z
y

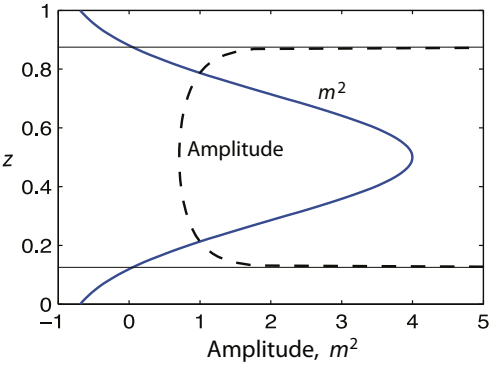

1
0.8
0.6
0.4
0.2
0
z
m^2
Amplitude
−1
0
1
2
3
4
5
Amplitude, m^2

Fig. 7.13

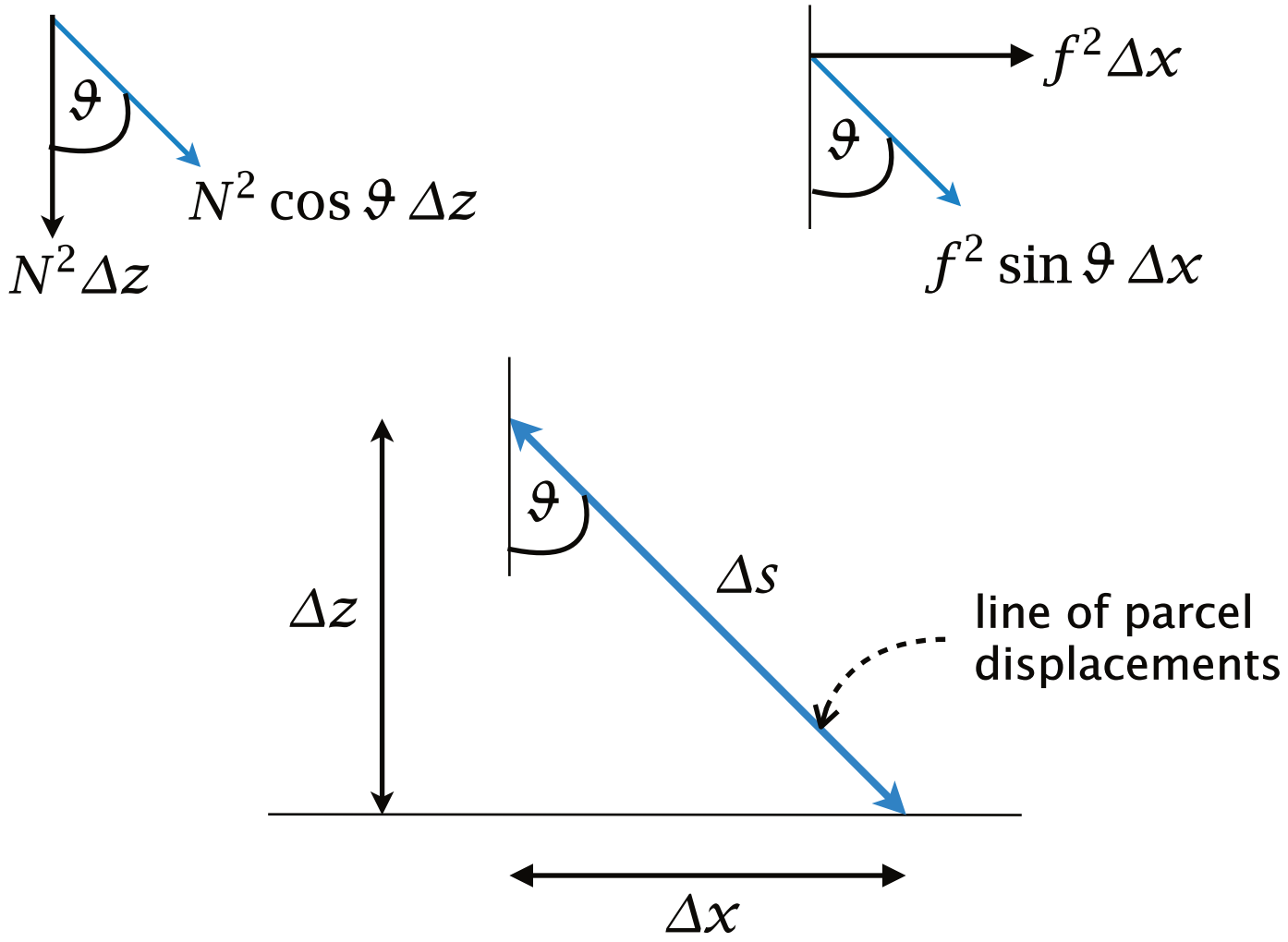

ϑ
$N^2 \cos\vartheta\, \Delta z$
$N^2 \Delta z$
$f^2 \Delta x$
ϑ
$f^2 \sin\vartheta\, \Delta x$
ϑ
Δz
Δs
line of parcel displacements
Δx

Fig. 7.14

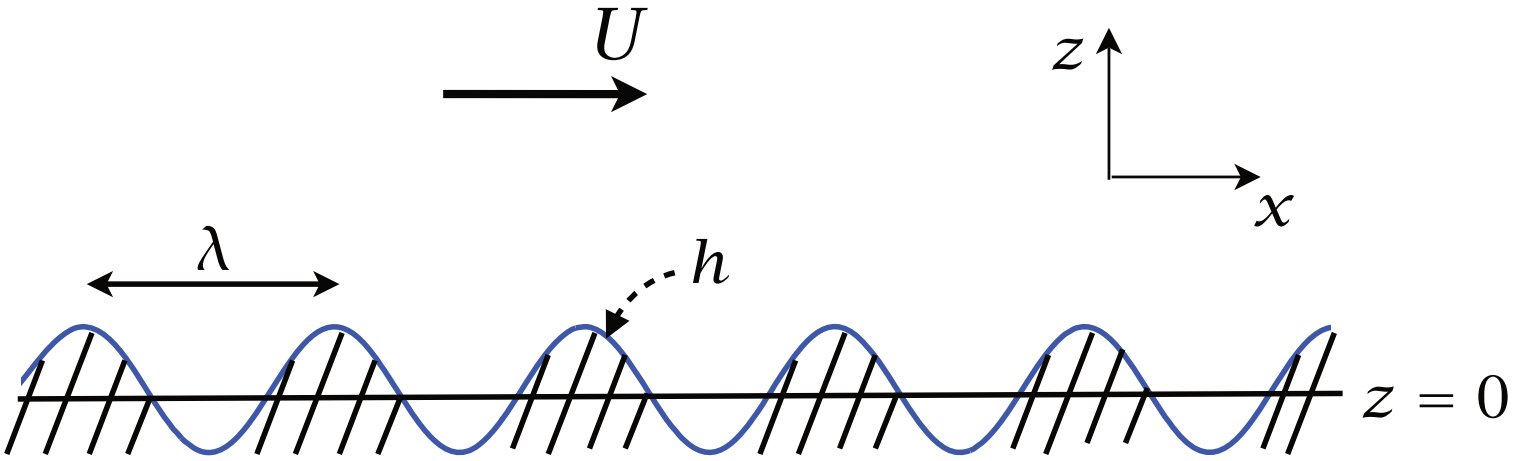


Fig. 7.15

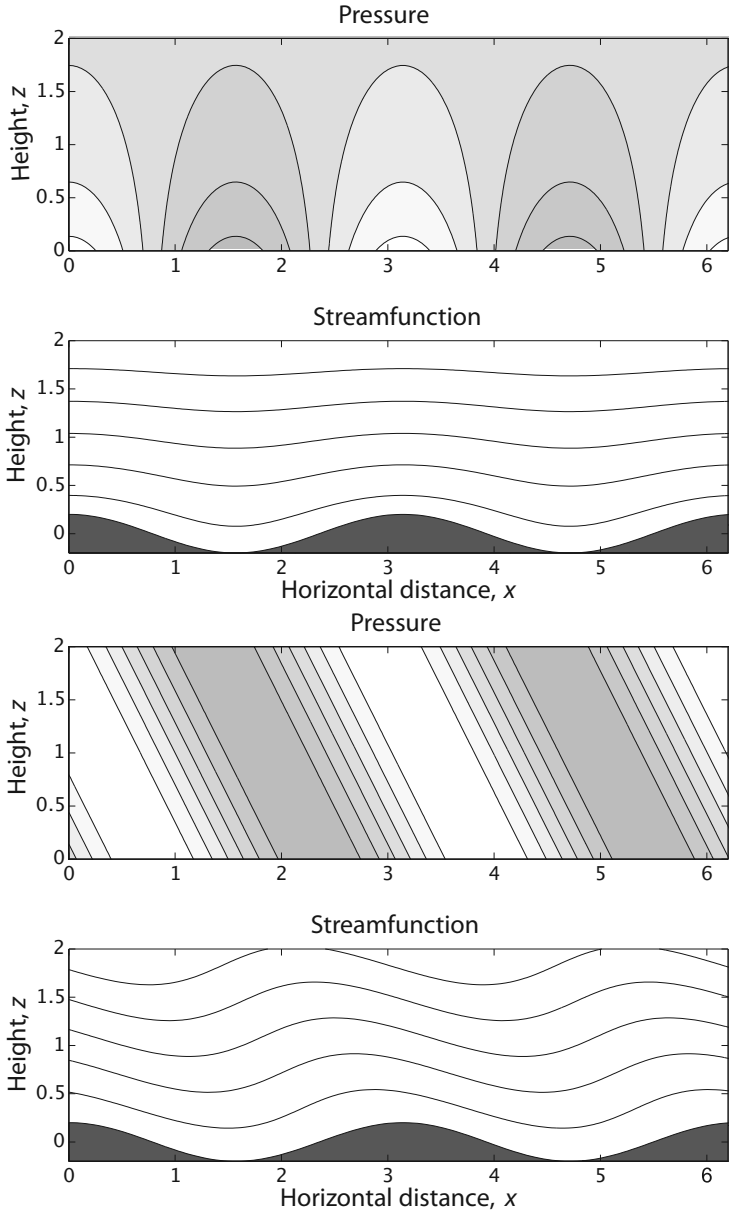

Pressure
Height, z
Streamfunction
Height, z
Horizontal distance, x
Pressure
Height, z
Streamfunction
Height, z
Horizontal distance, x

Fig. 7.16

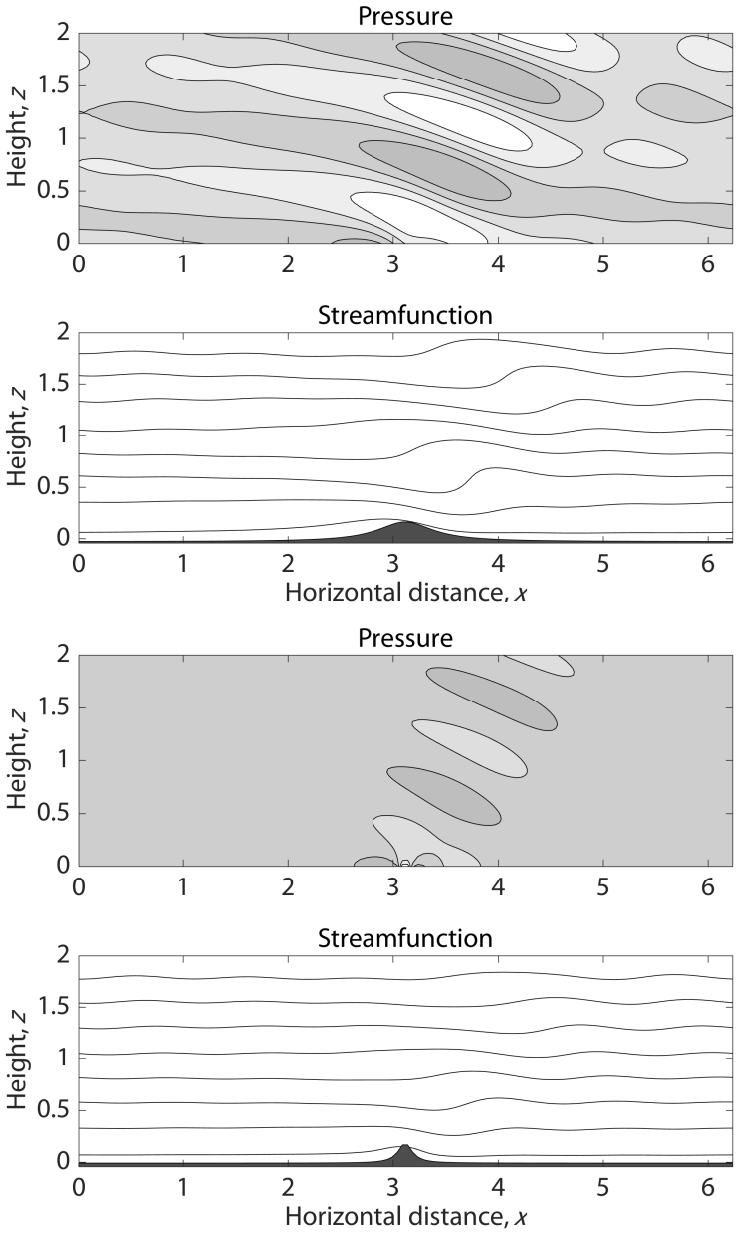

Pressure
Height, z
Streamfunction
Height, z
Horizontal distance, x
Pressure
Height, z
Streamfunction
Height, z
Horizontal distance, x

Fig. 7.17

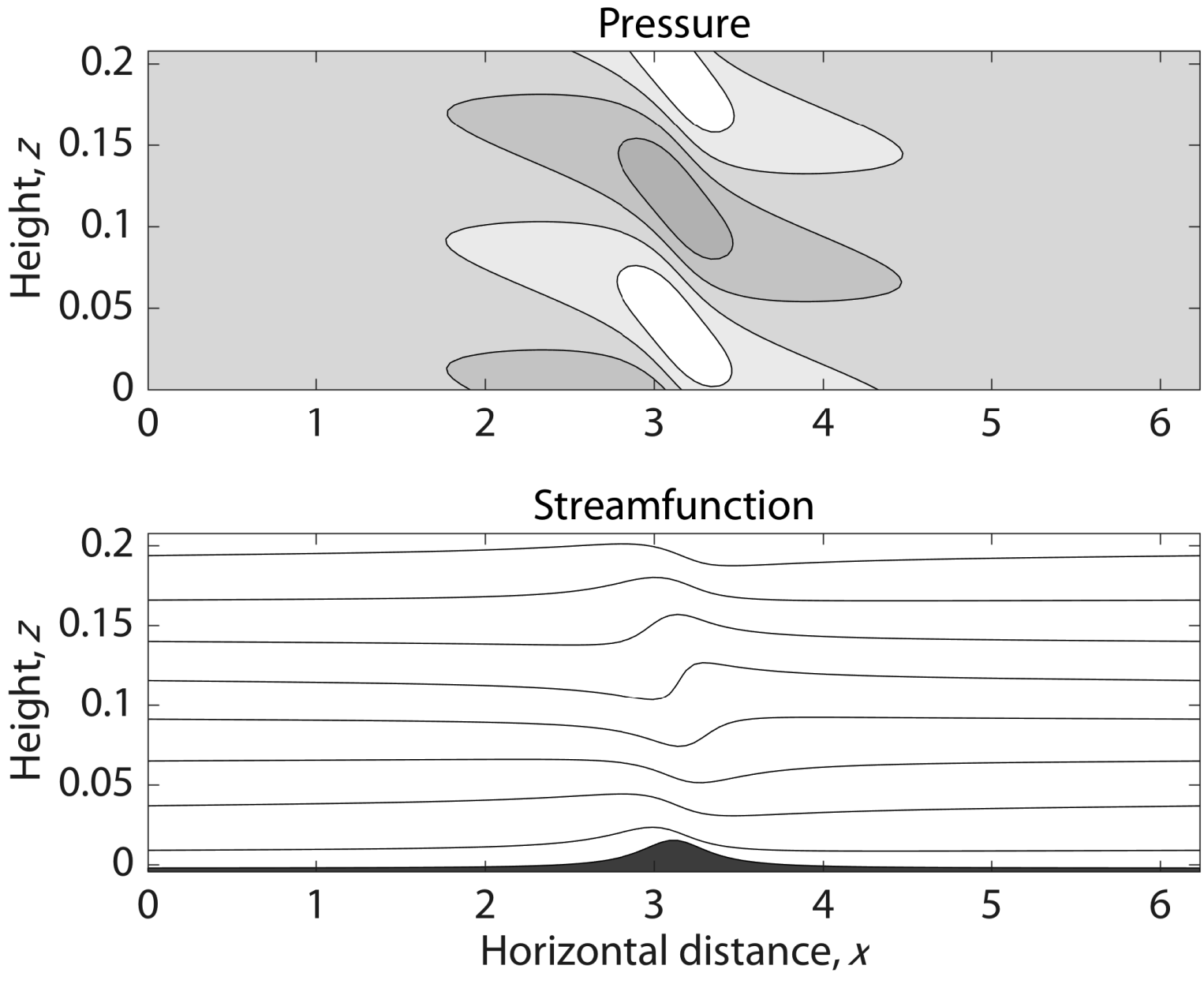

Pressure
Height, z
0.2
0.15
0.1
0.05
0
0
1
2
3
4
5
6
Streamfunction
Height, z
0.2
0.15
0.1
0.05
0
0
1
2
3
4
5
6
Horizontal distance, x

Fig. 7.18

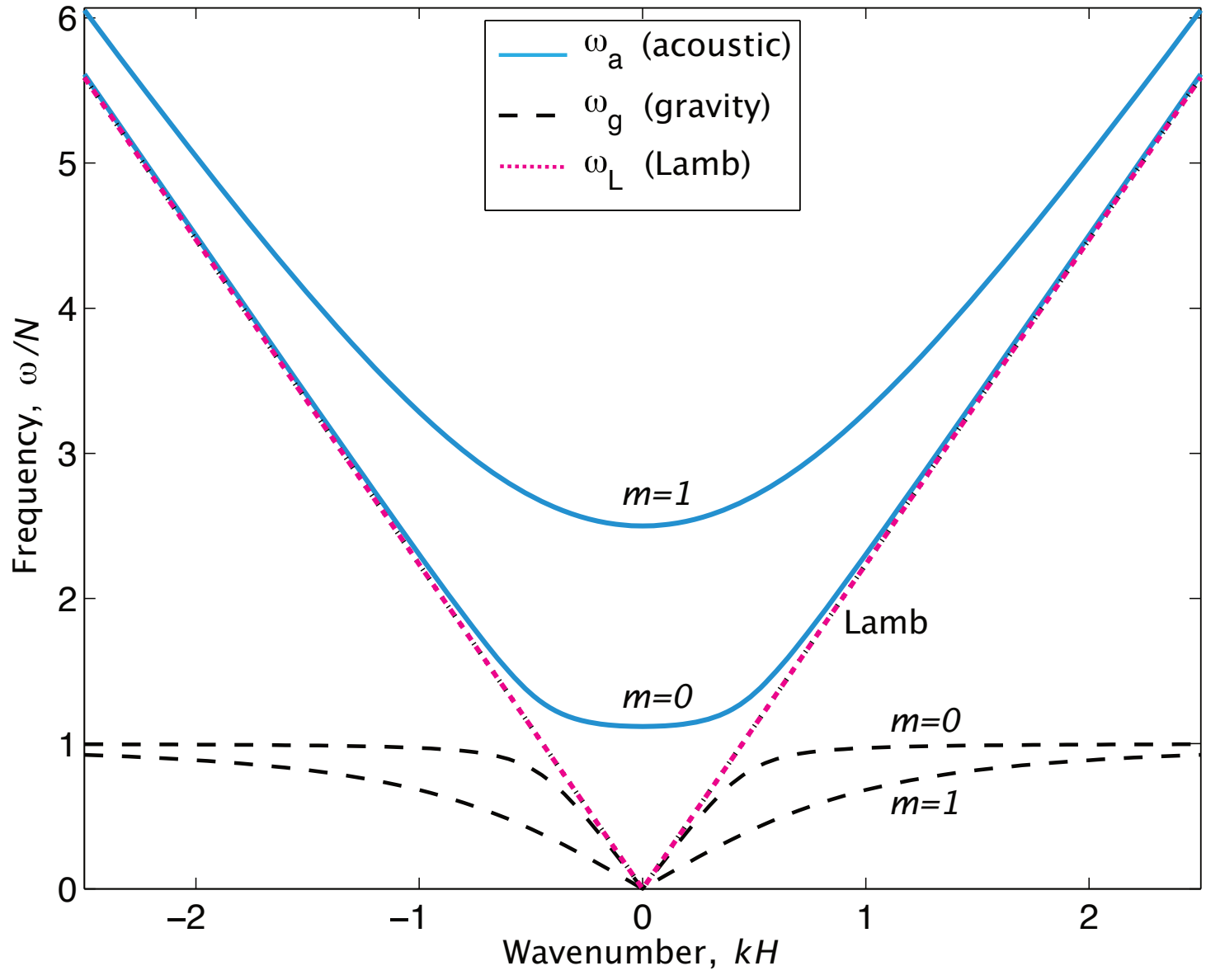
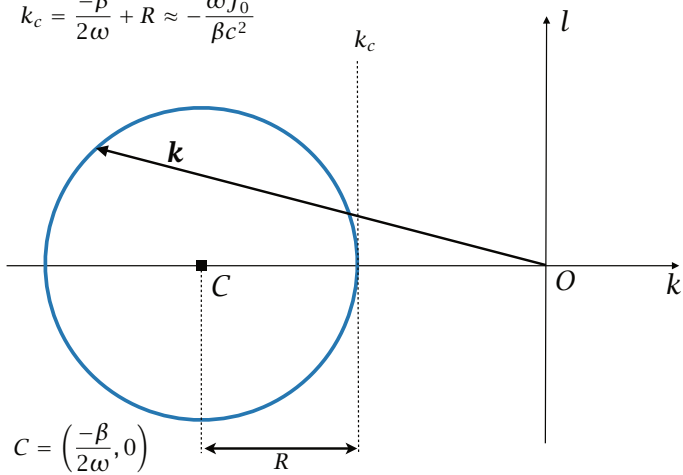

ω_a (acoustic)
ω_g (gravity)
ω_L (Lamb)
m=1
Lamb
m=0
m=0
m=1
Frequency, ω/N
Wavenumber, kH
0
1
2
3
4
5
6
−2
−1
0
1
2

Fig. 7.19

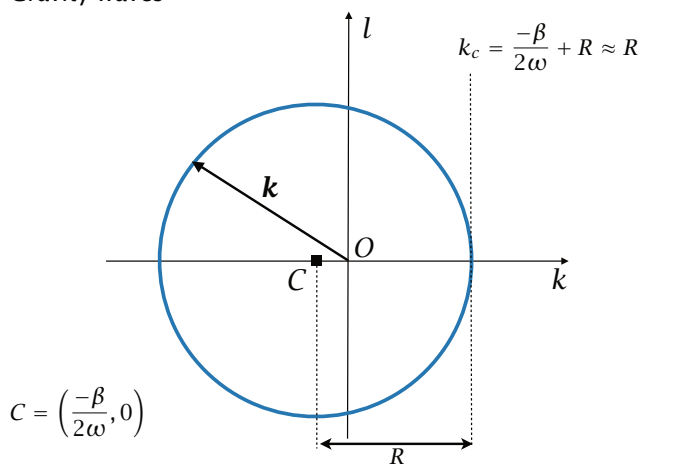
Rossby waves

$$k_c = \frac{-\beta}{2\omega} + R \approx -\frac{\omega f_0^2}{\beta c^2}$$



$$R = \left[\left(\frac{\beta}{2\omega}\right)^2 + \frac{\omega^2 - f_0^2}{c^2}\right]^{1/2} \approx \left[\left(\frac{\beta}{2\omega}\right)^2 - \frac{f_0^2}{c^2}\right]^{1/2}$$

Gravity waves



$$R = \left[\left(\frac{\beta}{2\omega}\right)^2 + \frac{\omega^2 - f_0^2}{c^2}\right]^{1/2} \approx \left[\frac{\omega^2 - f_0^2}{c^2}\right]^{1/2}$$

Fig. 8.1

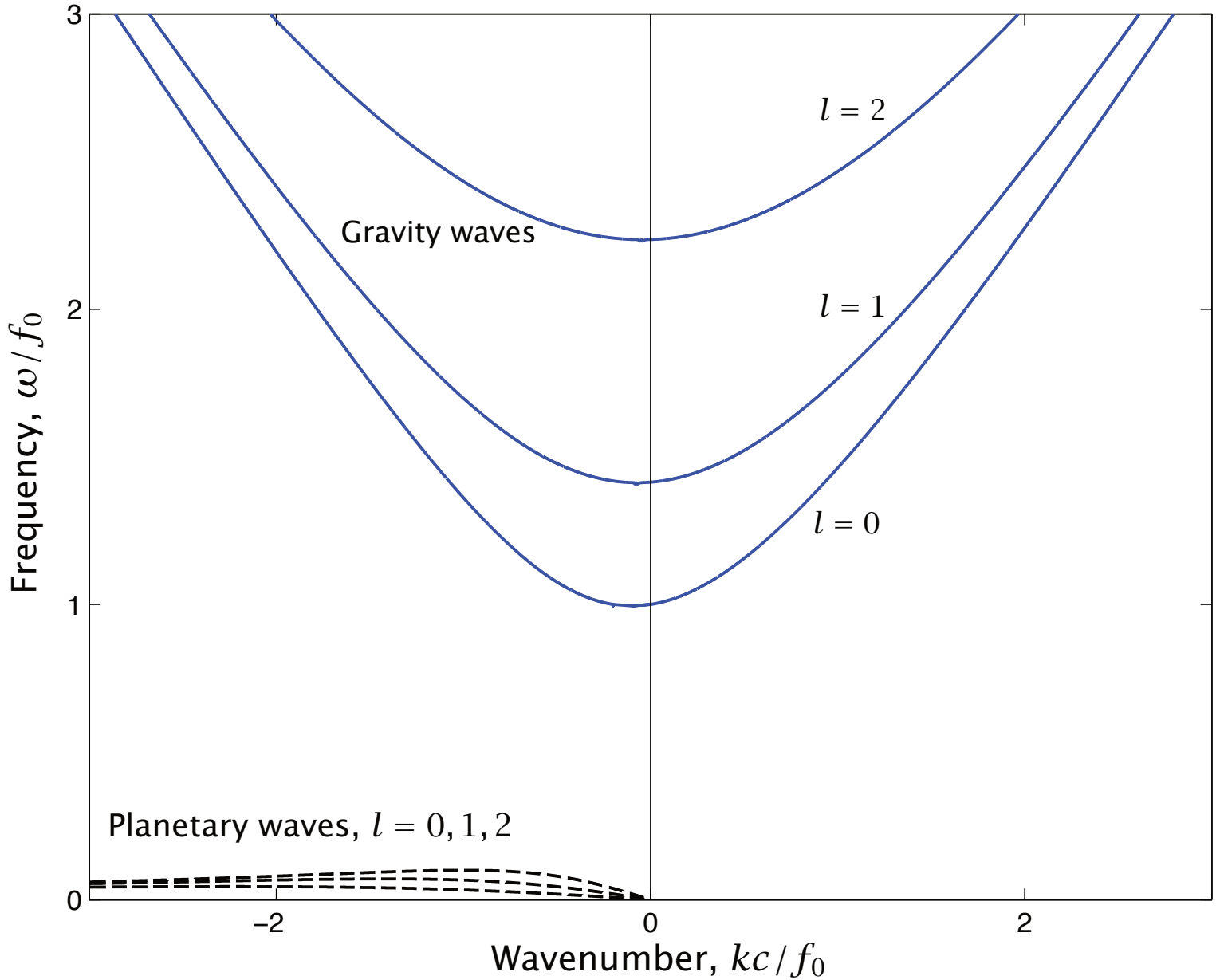

3
2
1
0
−2
0
2
Frequency, ω/f_0
Wavenumber, kc/f_0
$l = 2$
$l = 1$
$l = 0$
Gravity waves
Planetary waves, $l = 0, 1, 2$

Fig. 8.2

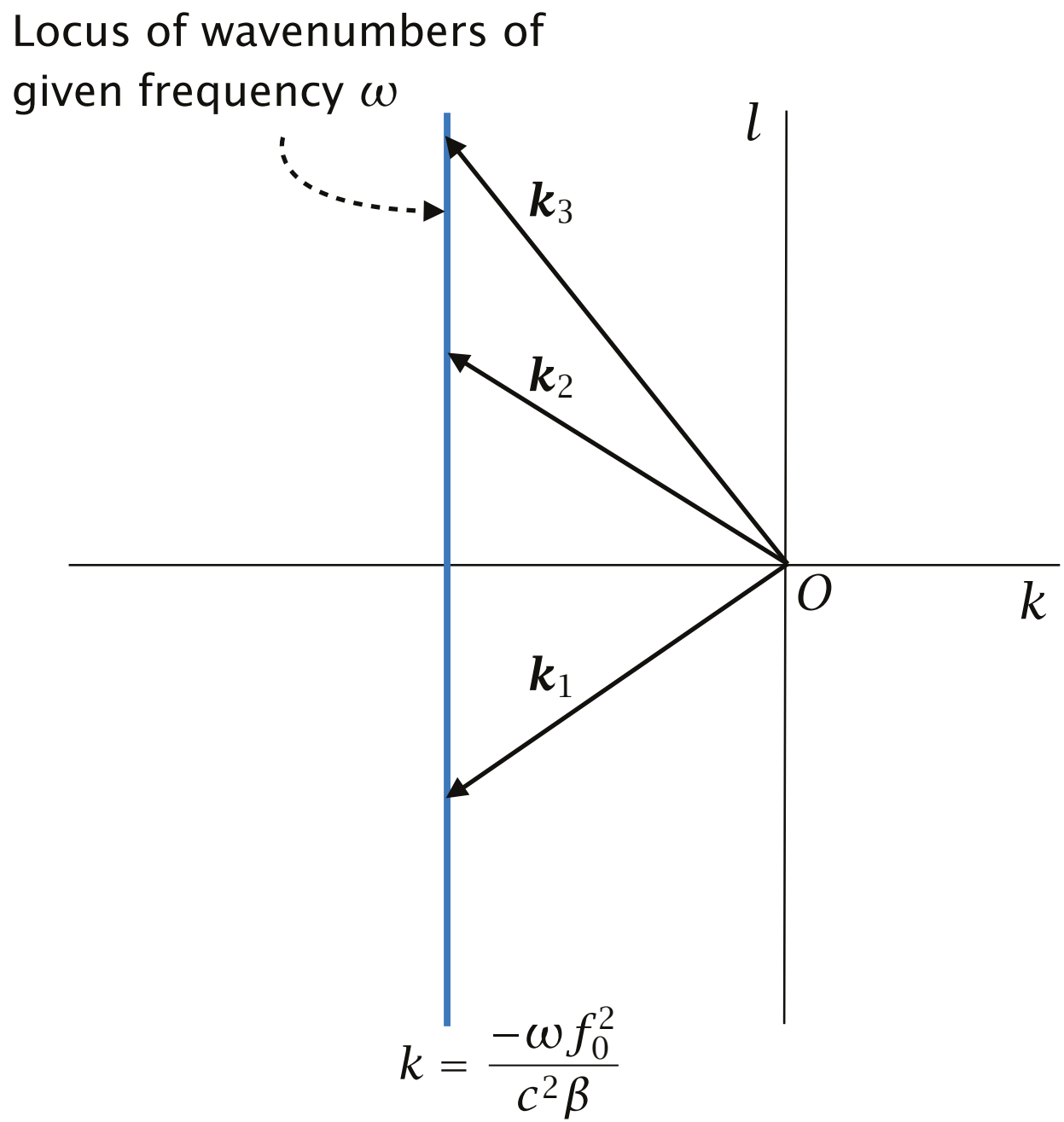

Locus of wavenumbers of
given frequency ω
l
$\boldsymbol{k}_3$
$\boldsymbol{k}_2$
O
k
$\boldsymbol{k}_1$
$k = \frac{-\omega f_0^2}{c^2 \beta}$

Fig. 8.3

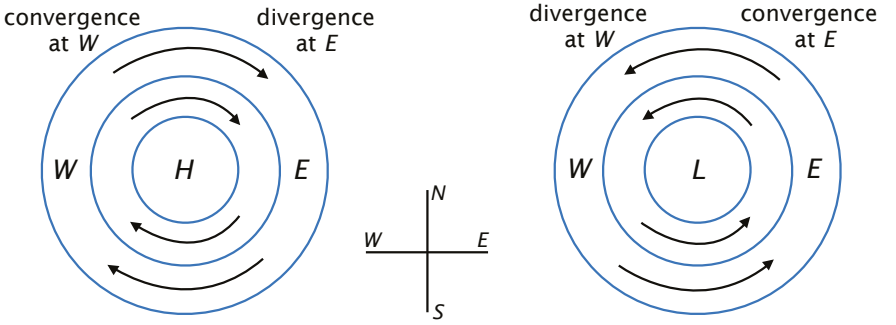

convergence at W
divergence at E
W
H
E
N
W
E
S
divergence at W
convergence at E
W
L
E

Fig. 8.4

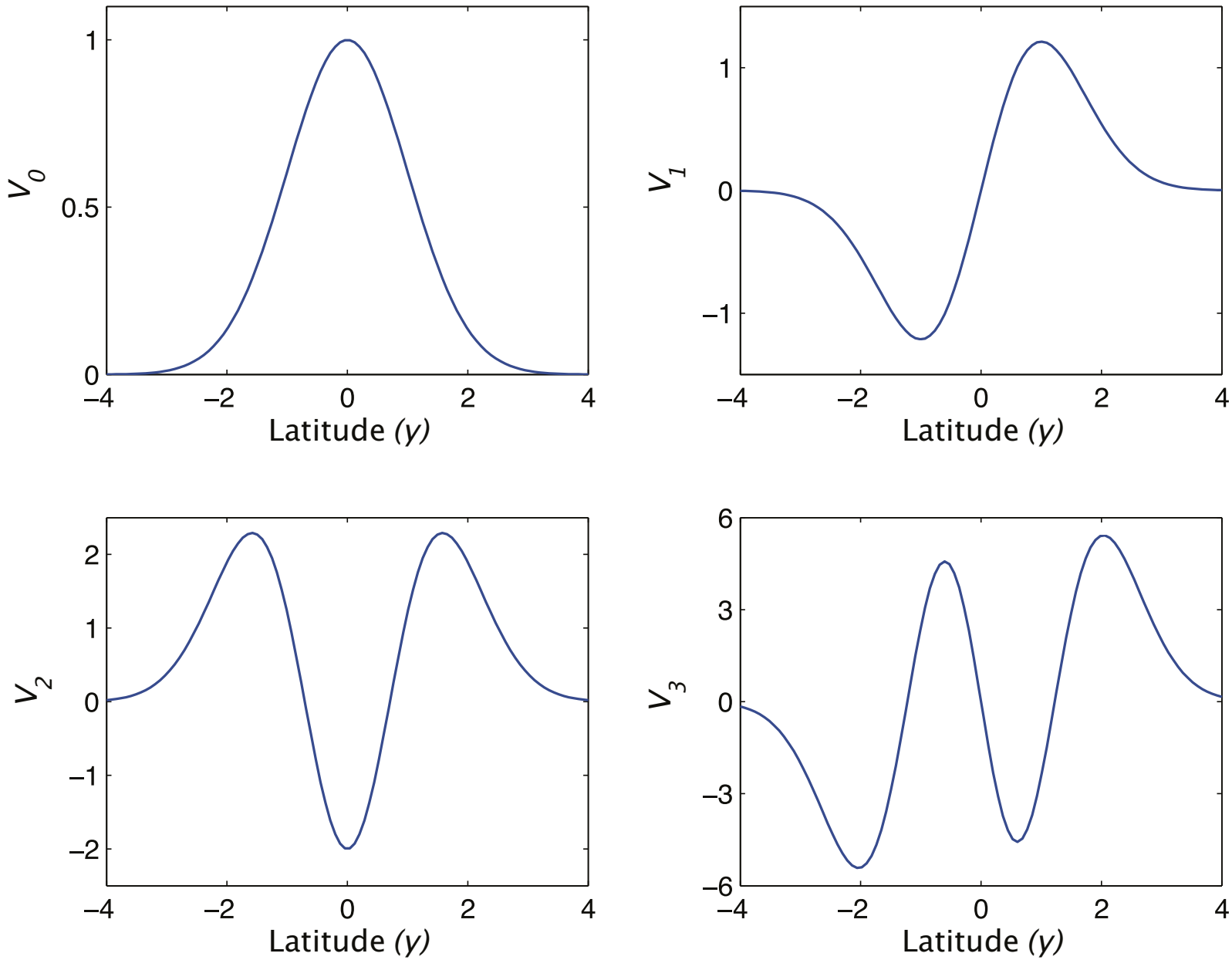

V_0
1
0.5
0
−4
−2
0
2
4
Latitude (y)
V_1
1
0
−1
−4
−2
0
2
4
Latitude (y)
V_2
2
1
0
−1
−2
−4
−2
0
2
4
Latitude (y)
V_3
6
3
0
−3
−6
−4
−2
0
2
4
Latitude (y)

Fig. 8.5

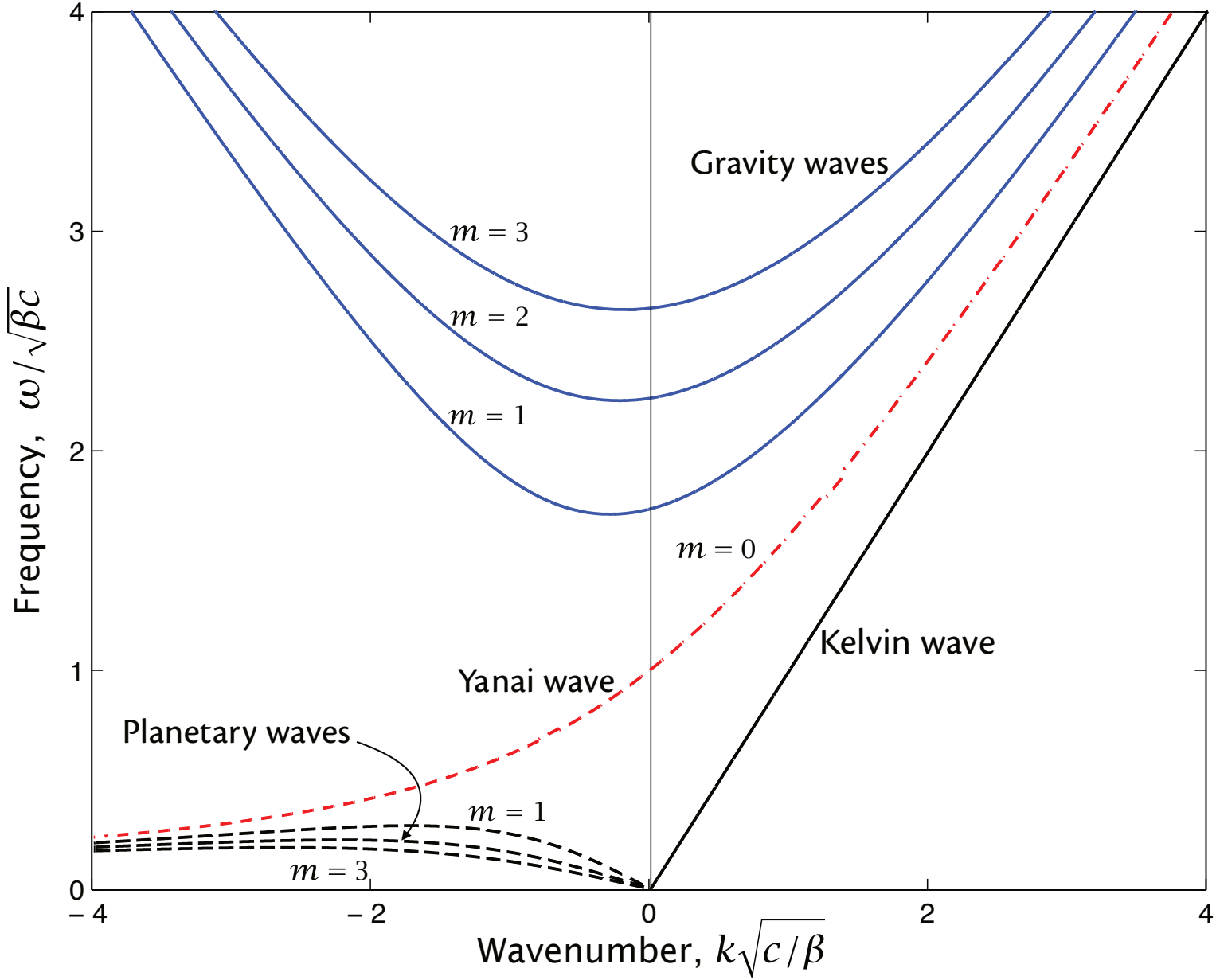

Gravity waves
$m = 3$
$m = 2$
$m = 1$
$m = 0$
Yanai wave
Kelvin wave
Planetary waves
$m = 1$
$m = 3$
Frequency, $\omega/\sqrt{\beta c}$
Wavenumber, $k\sqrt{c/\beta}$
4
3
2
1
0
– 4
– 2
0
2
4

Fig. 8.6

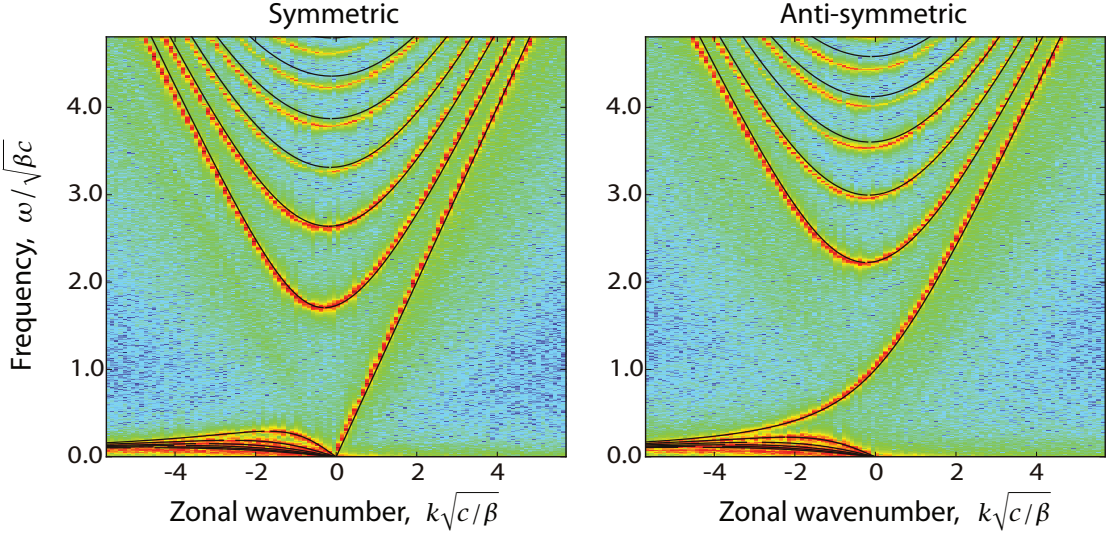

Symmetric
Anti-symmetric
Frequency, $\omega/\sqrt{\beta c}$
0.0
1.0
2.0
3.0
4.0
-4
-2
0
2
4
Zonal wavenumber, $k\sqrt{c/\beta}$
Zonal wavenumber, $k\sqrt{c/\beta}$

Fig. 8.7

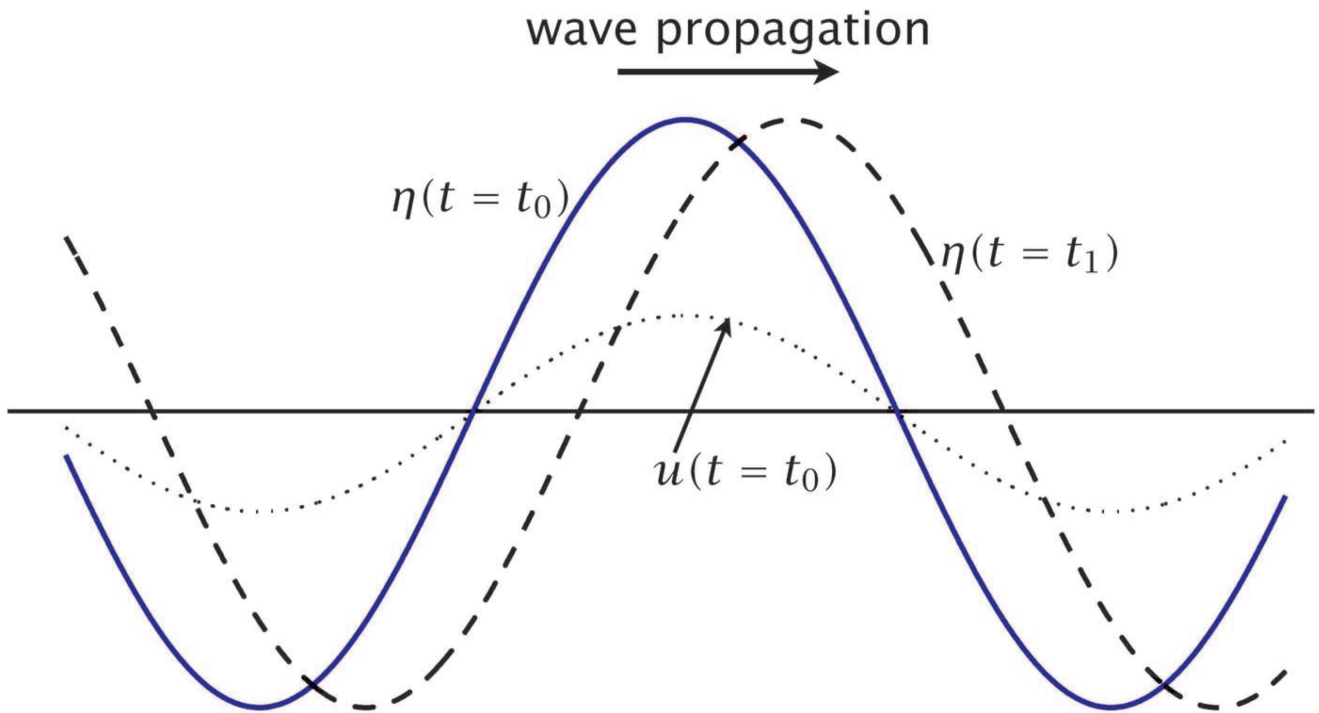


Fig. 8.8

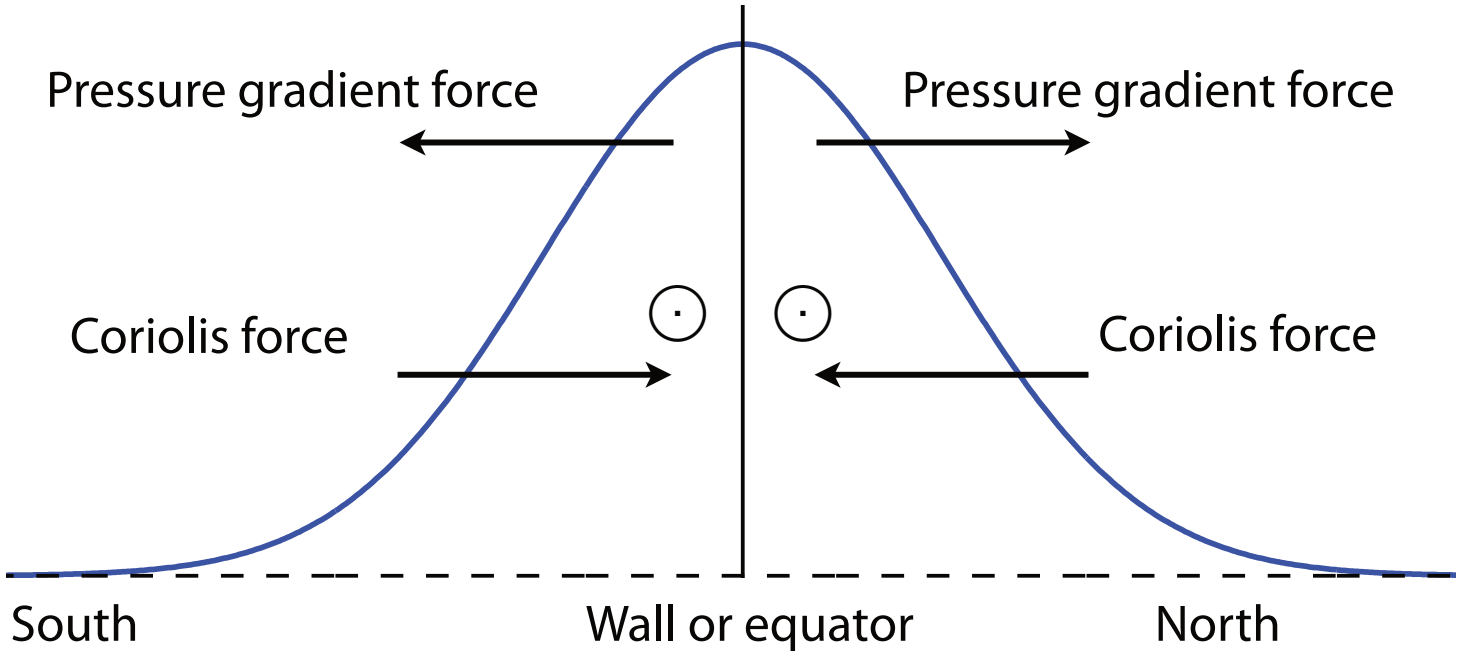

Pressure gradient force
Pressure gradient force
Coriolis force
Coriolis force
South
Wall or equator
North

Fig. 8.9

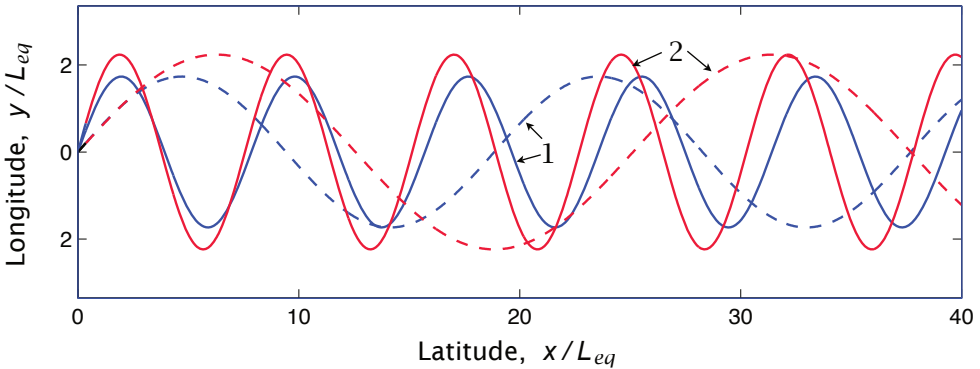


Fig. 8.10

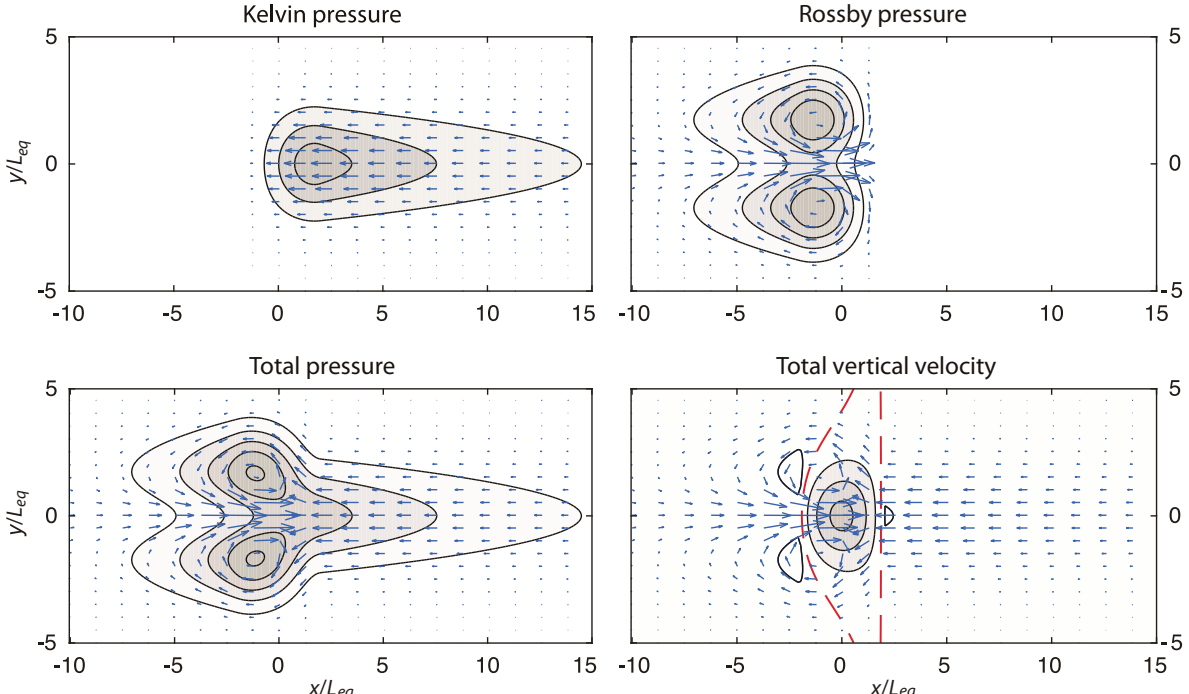

Kelvin pressure
Rossby pressure
Total pressure
Total vertical velocity
y/L_eq
x/L_eq
5
0
-5
-10
-5
0
5
10
15

Fig. 8.11

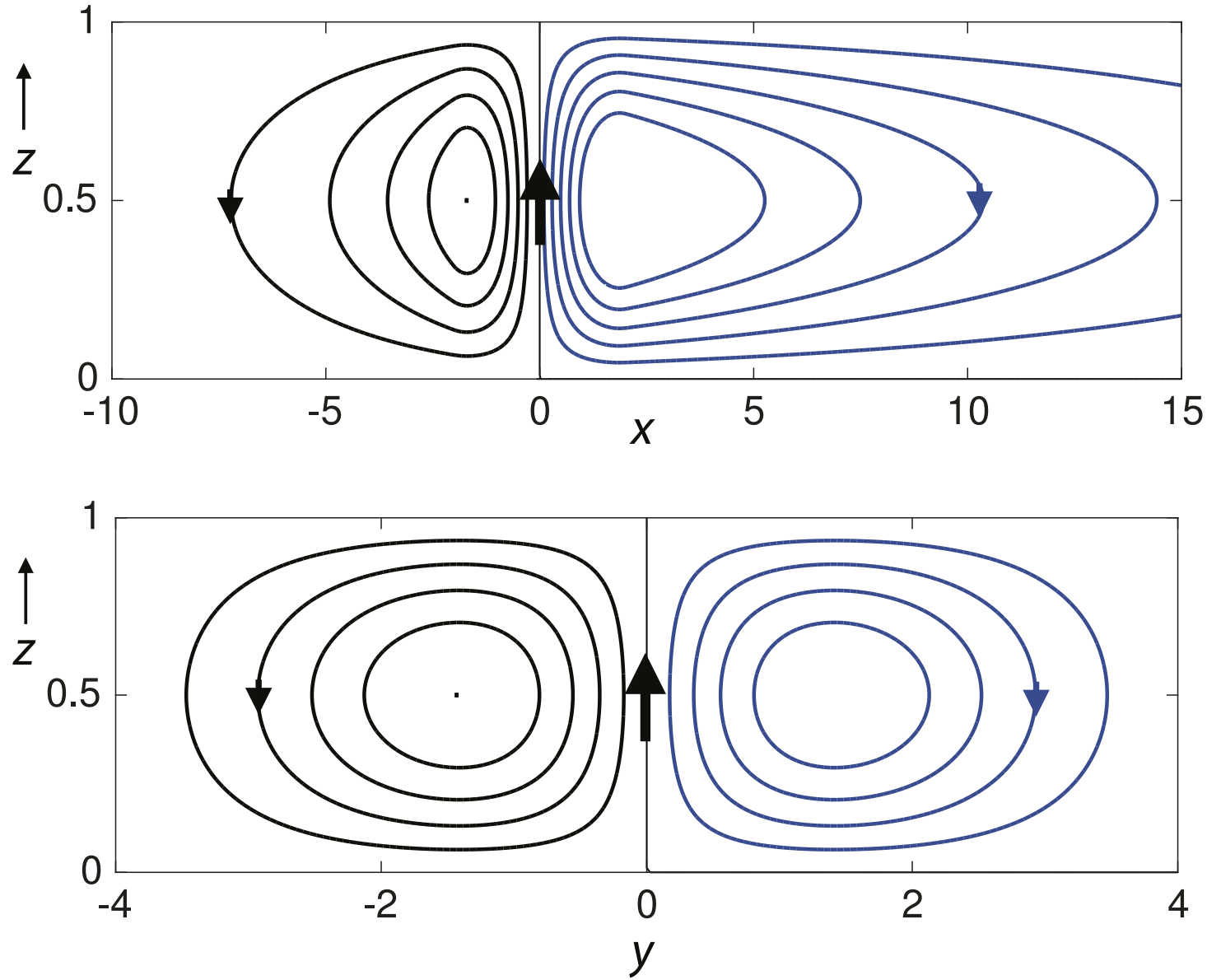


Fig. 8.12

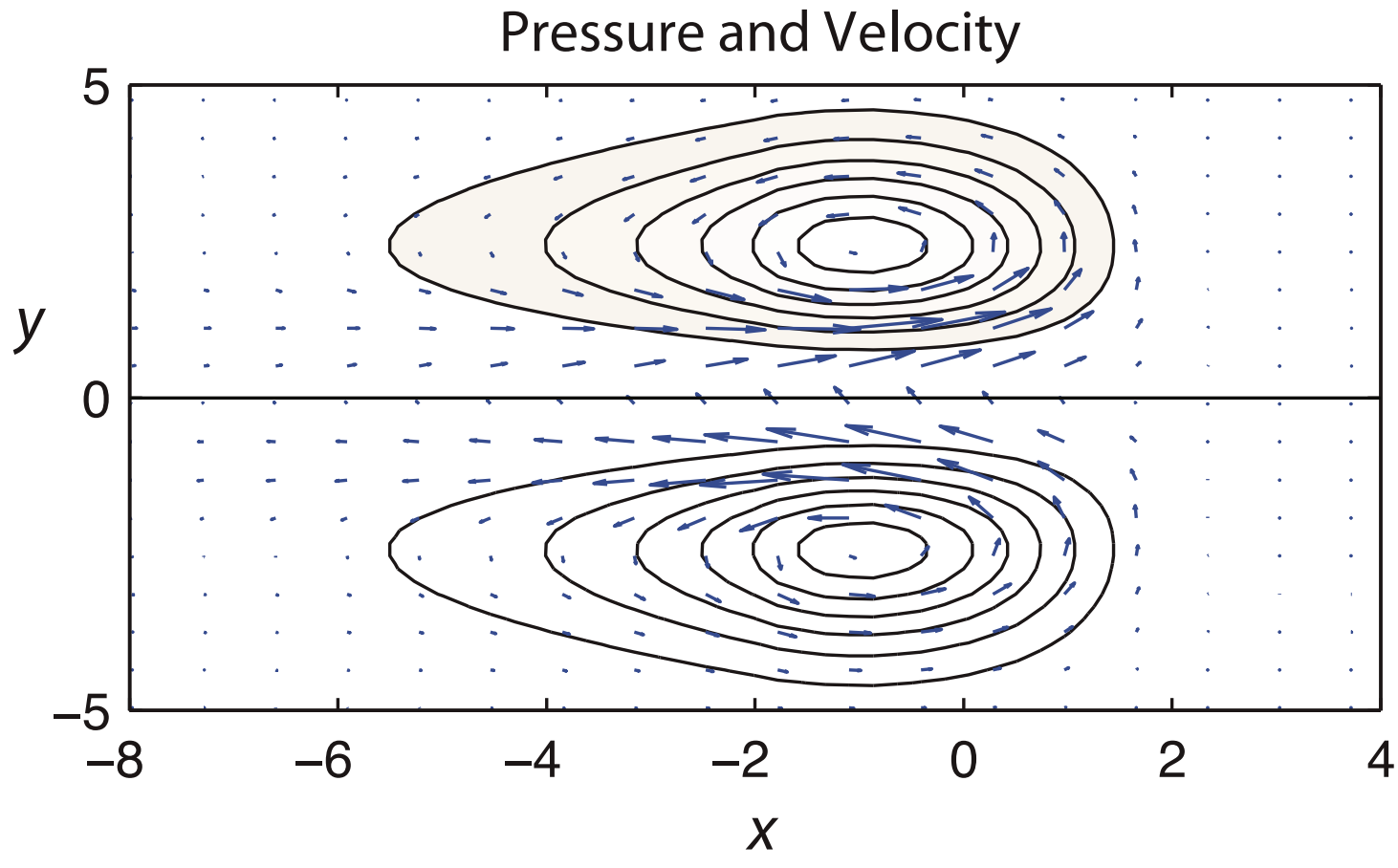


Fig. 8.13

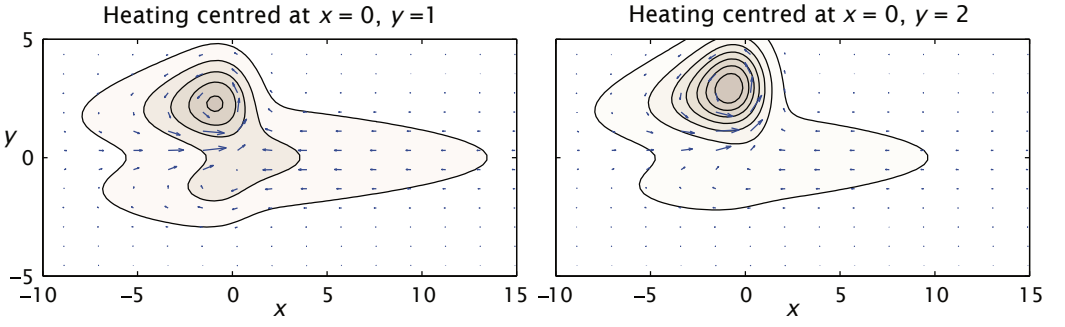

Heating centred at $x = 0$, $y = 1$
Heating centred at $x = 0$, $y = 2$
y
x
5
0
−5
−10
−5
0
5
10
15

Fig. 8.14

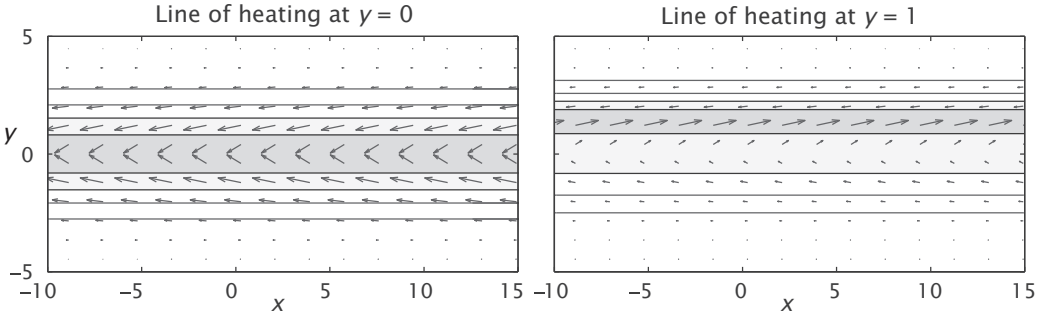


Fig. 8.15

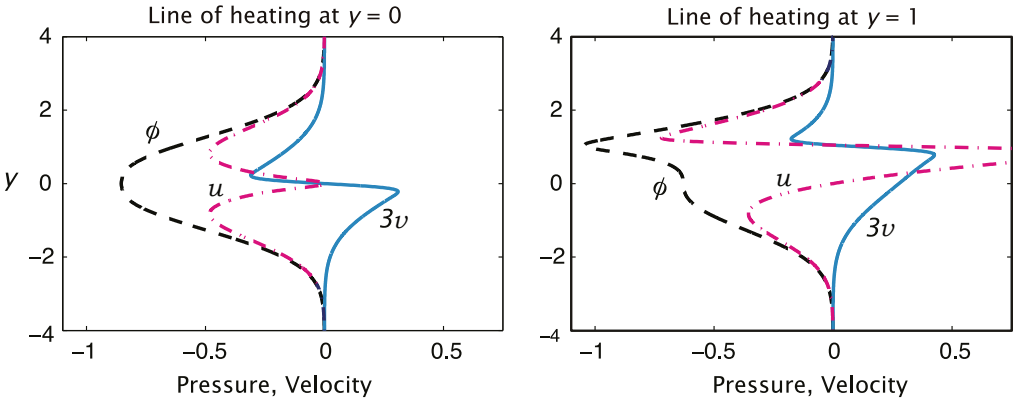

Line of heating at $y = 0$
Line of heating at $y = 1$
y
ϕ
u
$3v$
Pressure, Velocity
4
2
0
−2
−4
−1
−0.5
0
0.5

Fig. 8.16

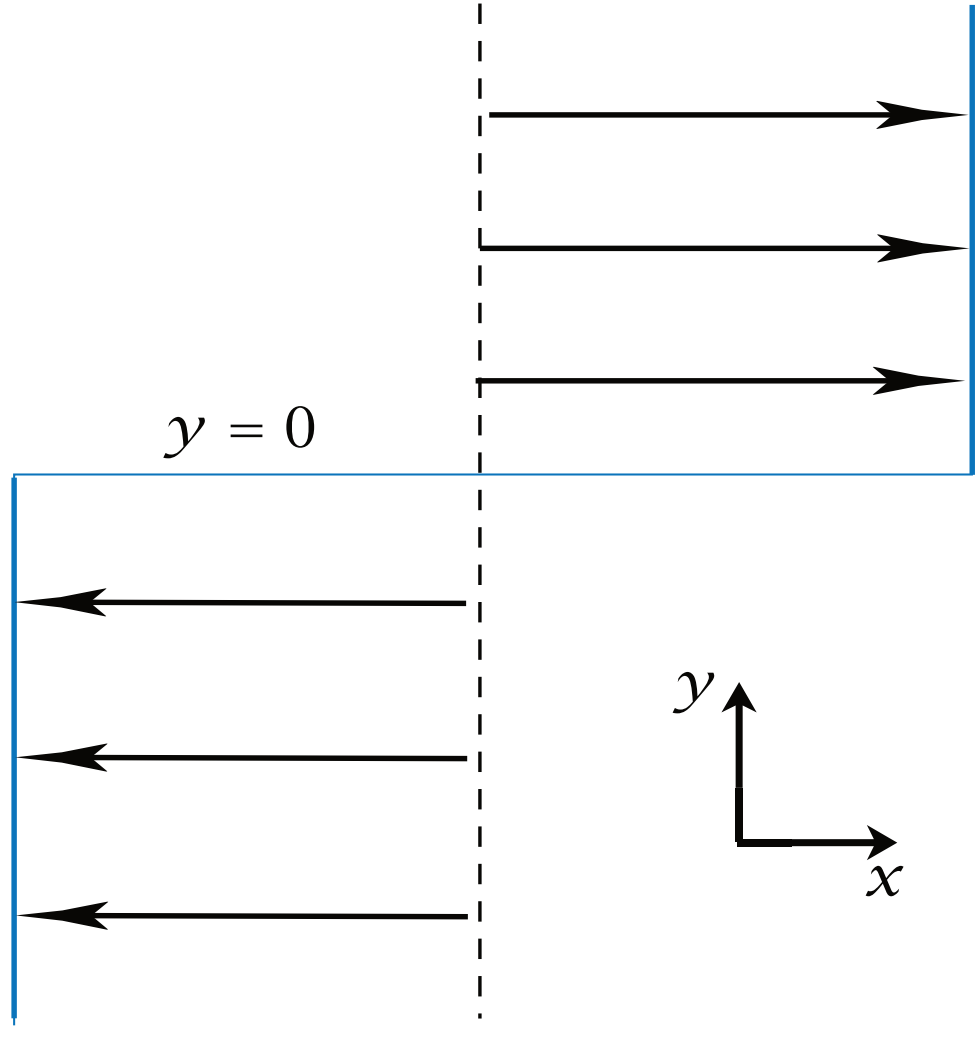


Fig. 9.1

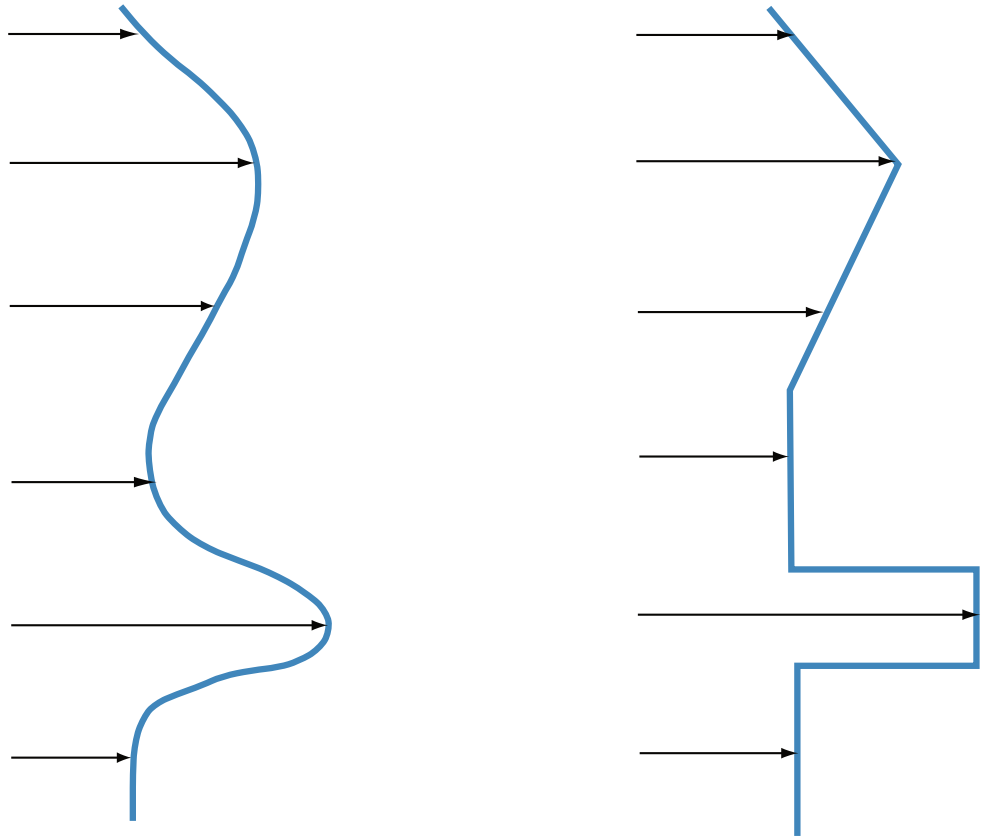


Fig. 9.2

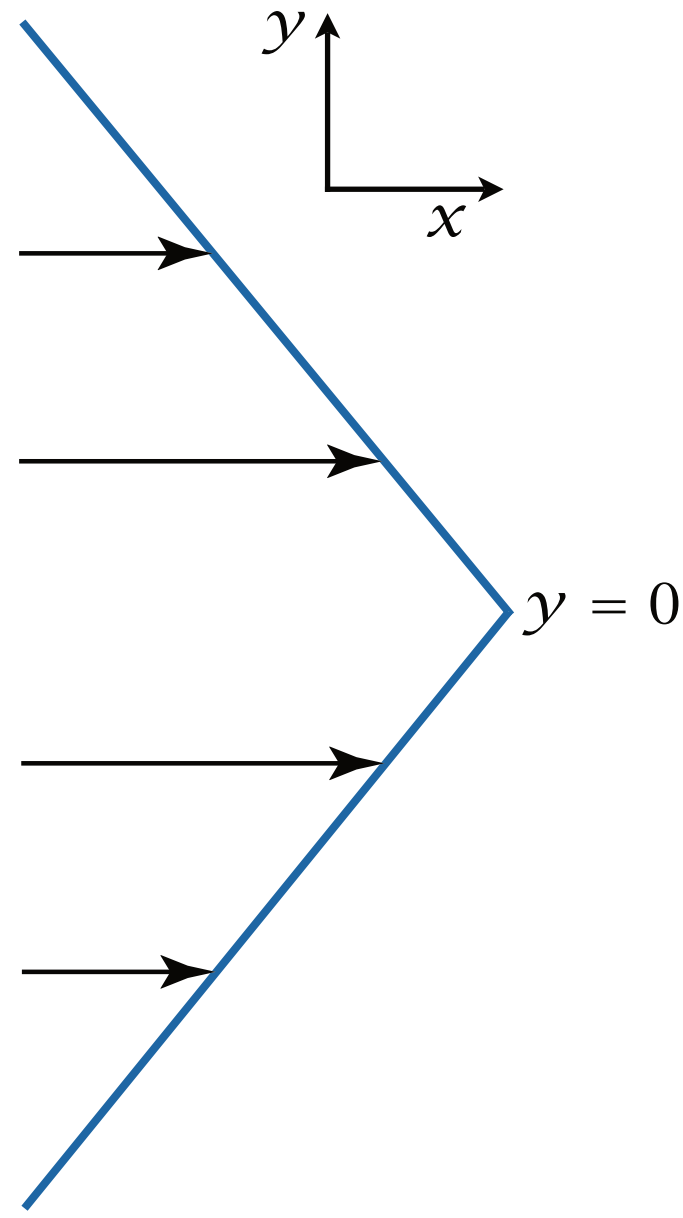


Fig. 9.3

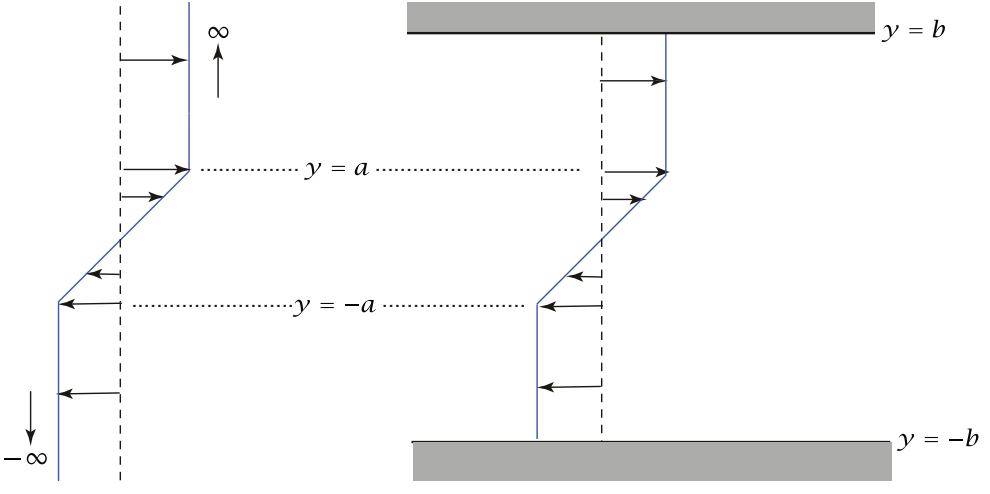
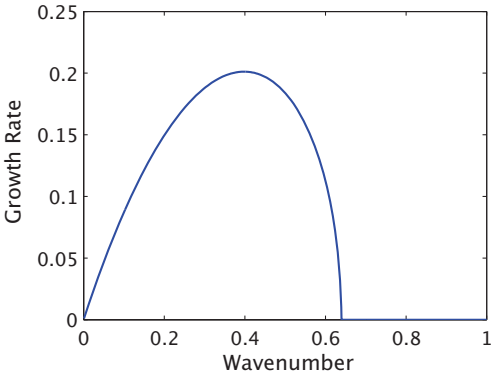


Fig. 9.4


0.25
0.2
0.15
0.1
0.05
0
Growth Rate
0
0.2
0.4
0.6
0.8
1
Wavenumber

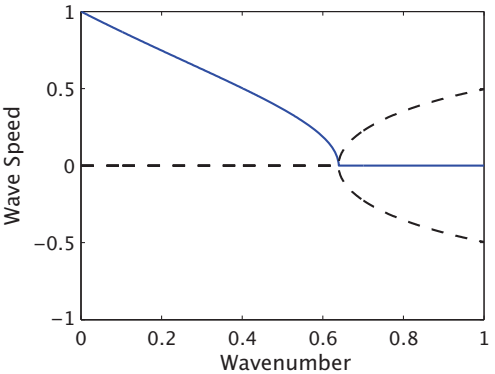

1
0.5
0
−0.5
−1
Wave Speed
0
0.2
0.4
0.6
0.8
1
Wavenumber

Fig. 9.5

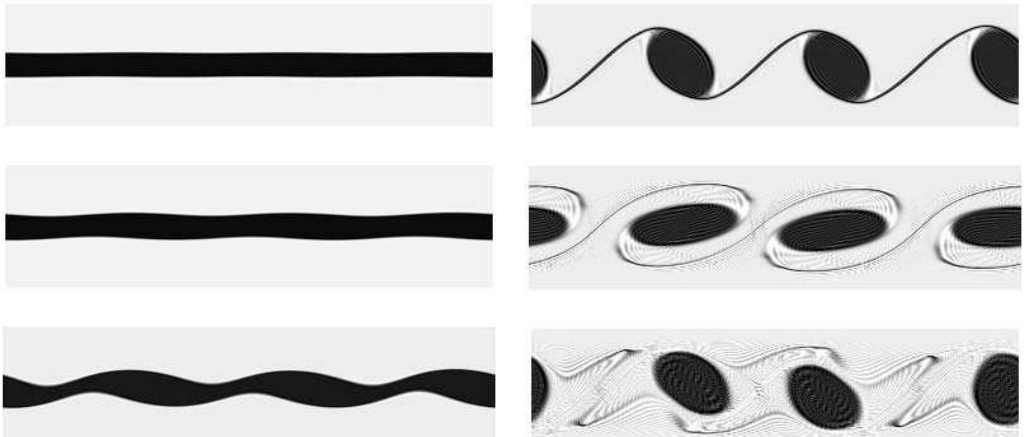


Fig. 9.6

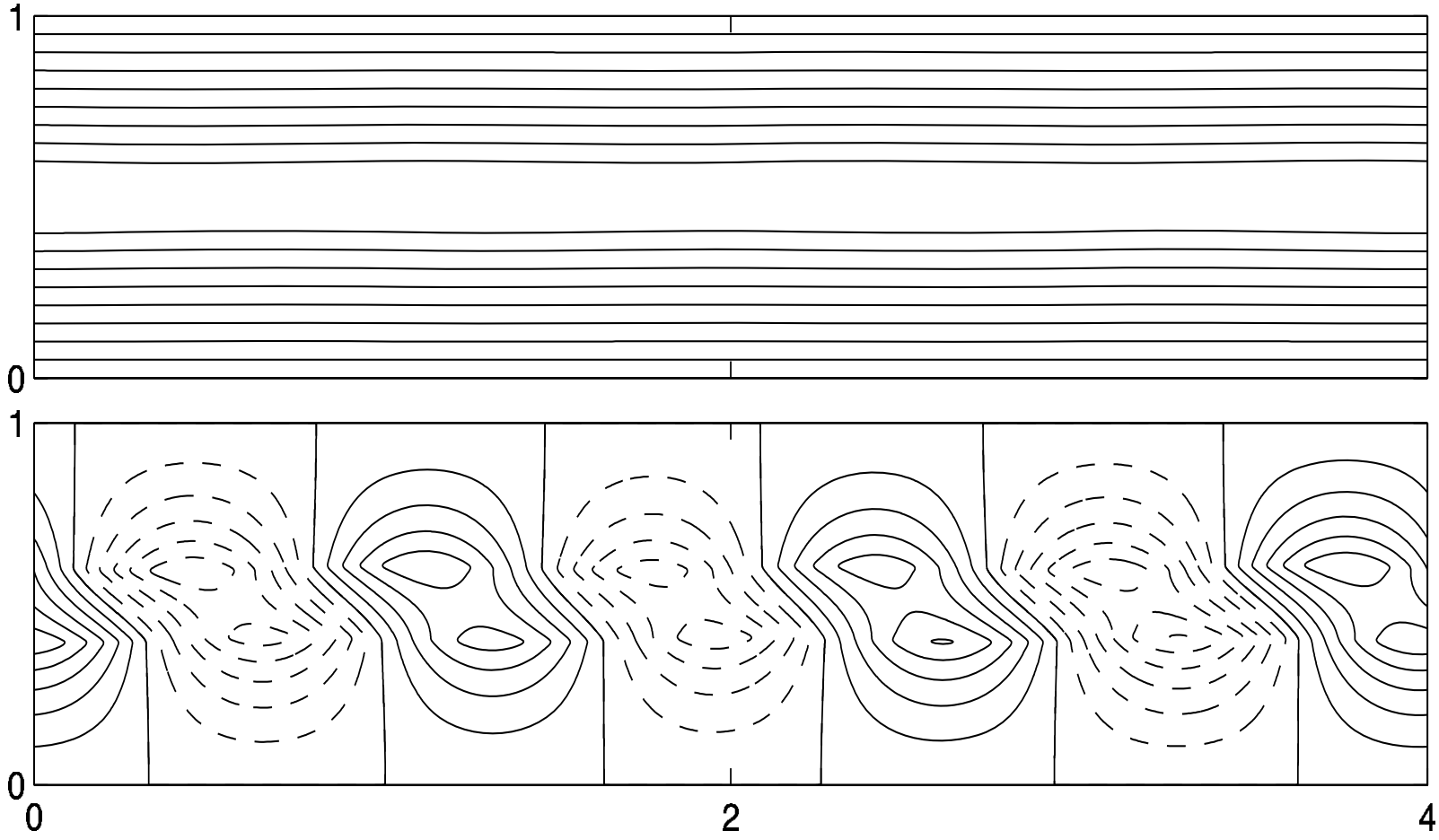


Fig. 9.7

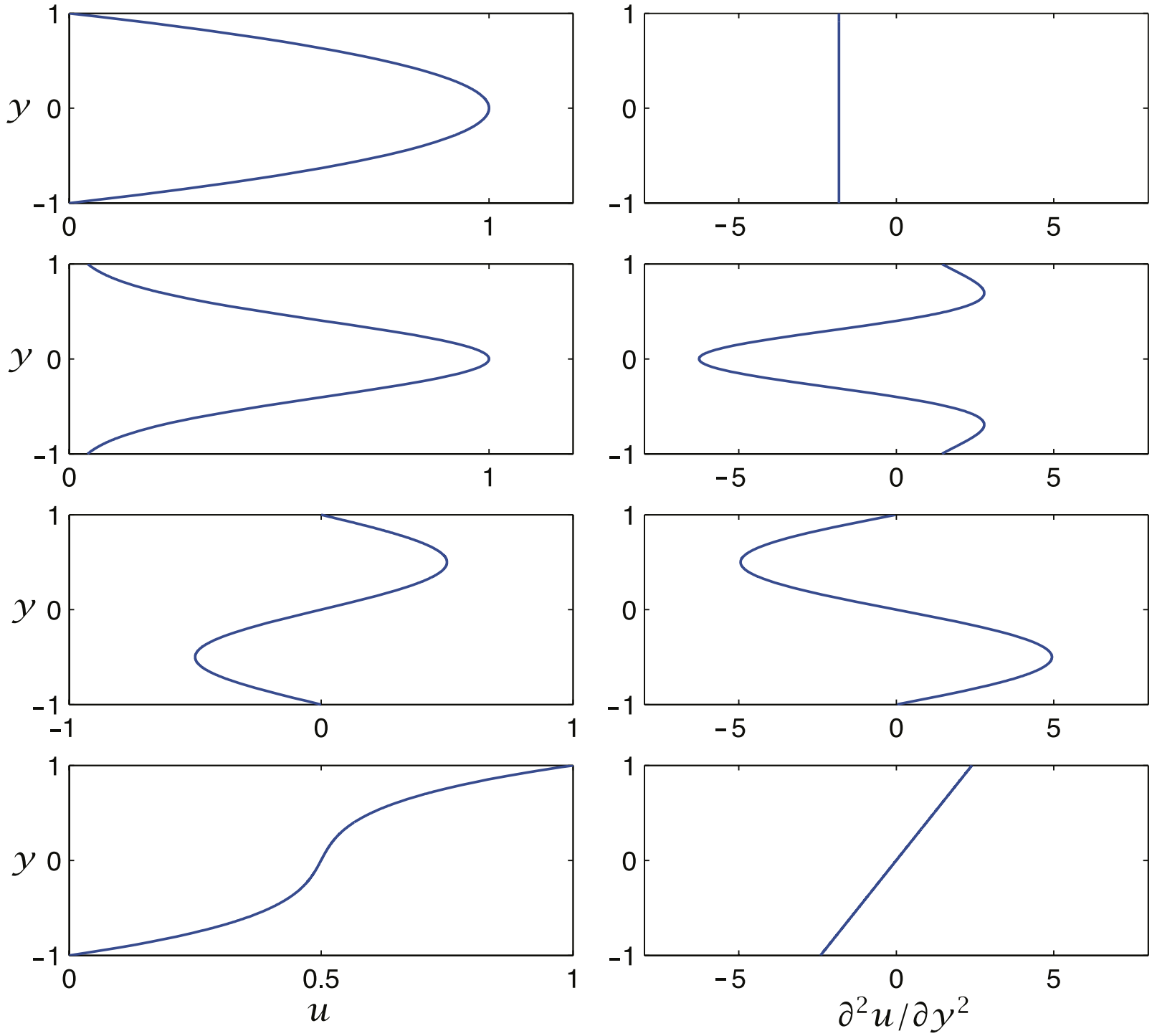


Fig. 9.8

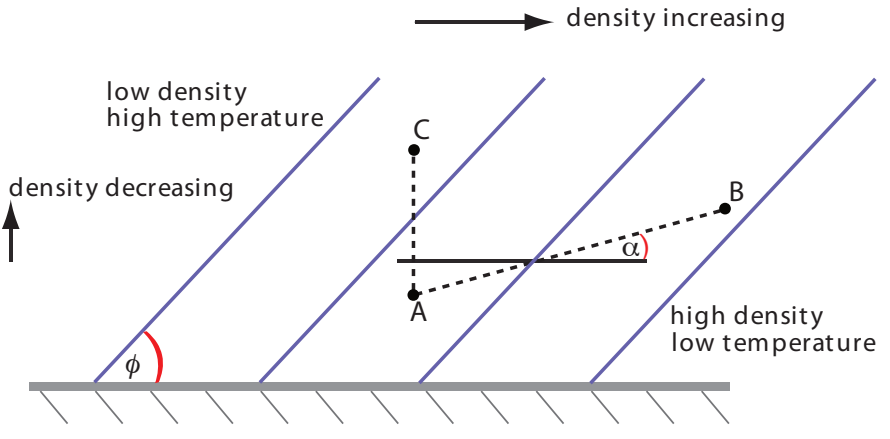

density increasing
low density
high temperature
density decreasing
C
B
α
A
high density
low temperature
ϕ

Fig. 9.9

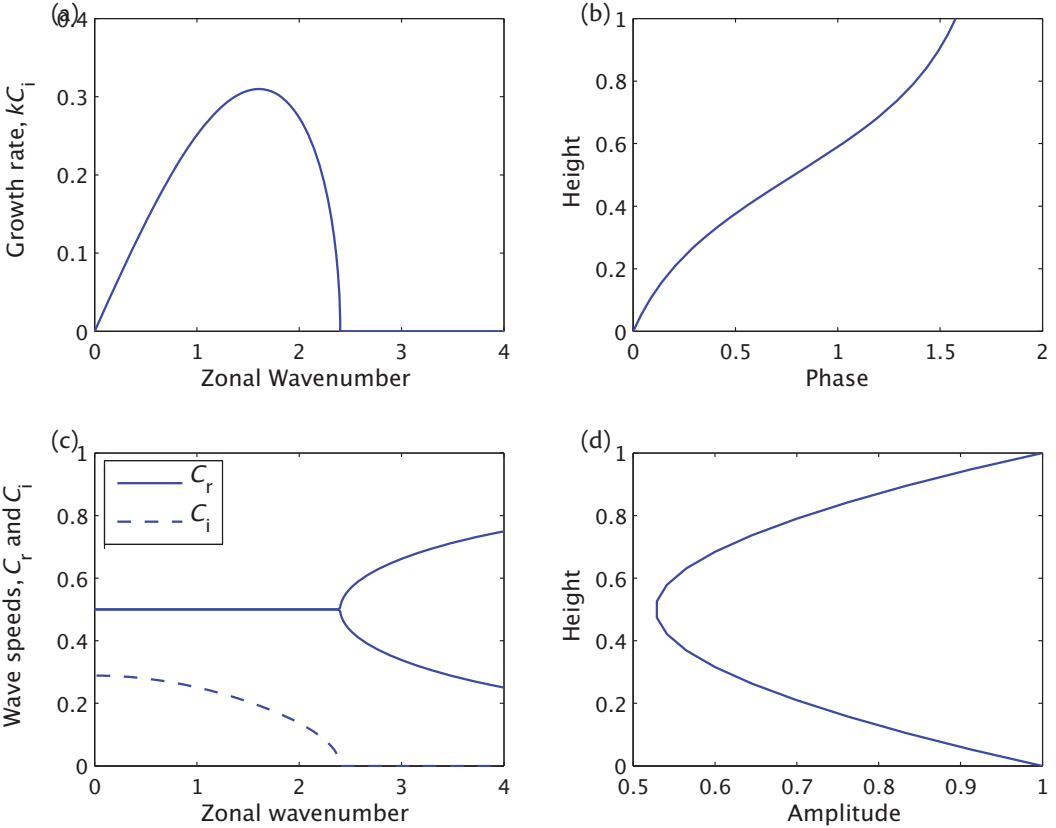

(a)
Growth rate, kC_i
Zonal Wavenumber
0
0.1
0.2
0.3
0.4
0
1
2
3
4
(b)
Height
Phase
0
0.2
0.4
0.6
0.8
1
0
0.5
1
1.5
2
(c)
Wave speeds, C_r and C_i
C_r
C_i
Zonal wavenumber
0
0.2
0.4
0.6
0.8
1
0
1
2
3
4
(d)
Height
Amplitude
0
0.2
0.4
0.6
0.8
1
0.5
0.6
0.7
0.8
0.9
1

Fig. 9.10

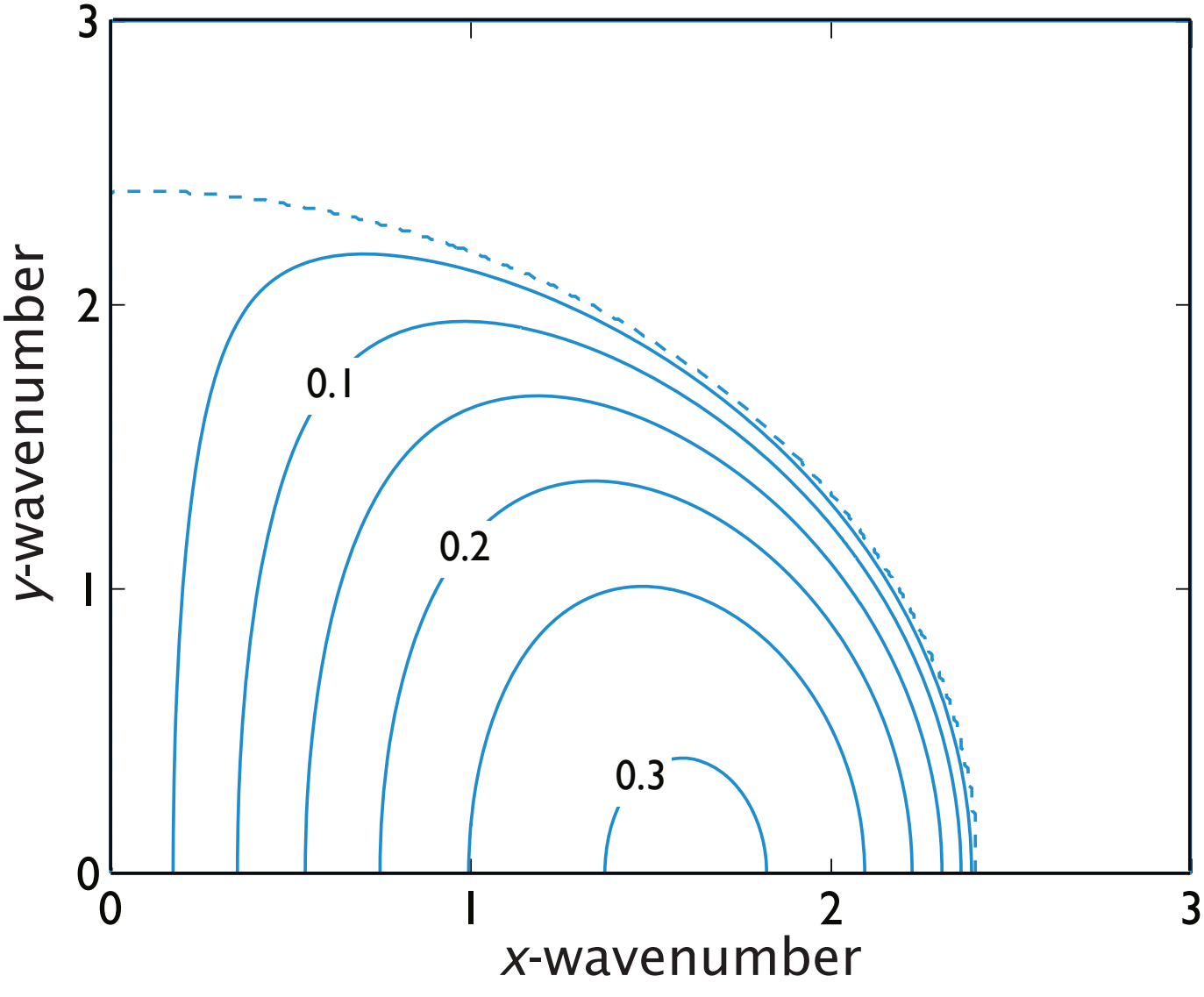


Fig. 9.11

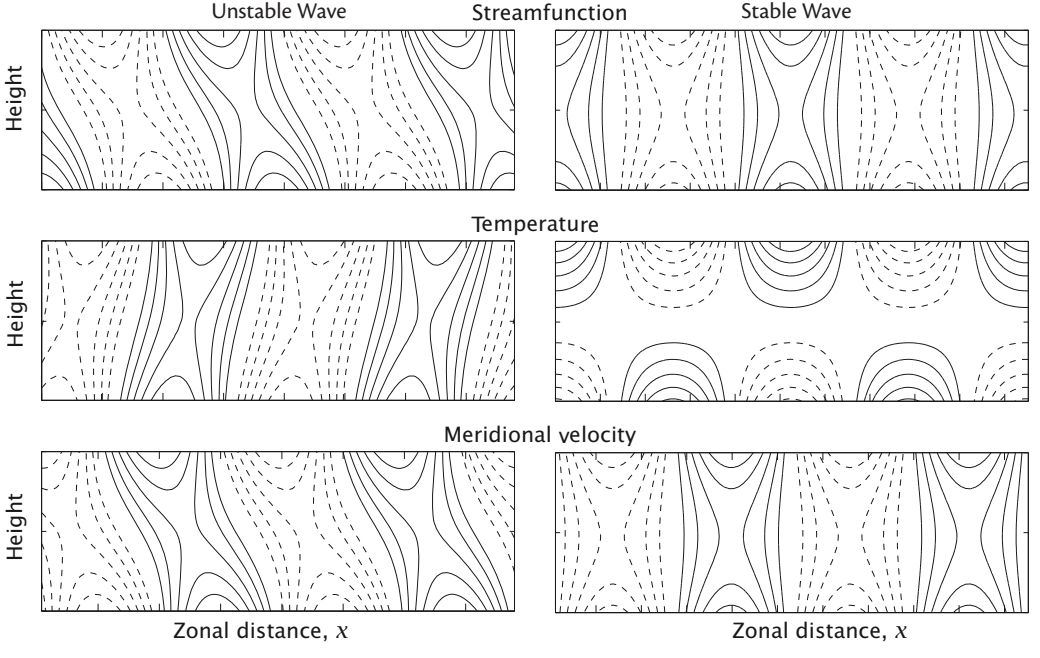

Unstable Wave
Streamfunction
Stable Wave
Height
Temperature
Height
Meridional velocity
Height
Zonal distance, x
Zonal distance, x

Fig. 9.12

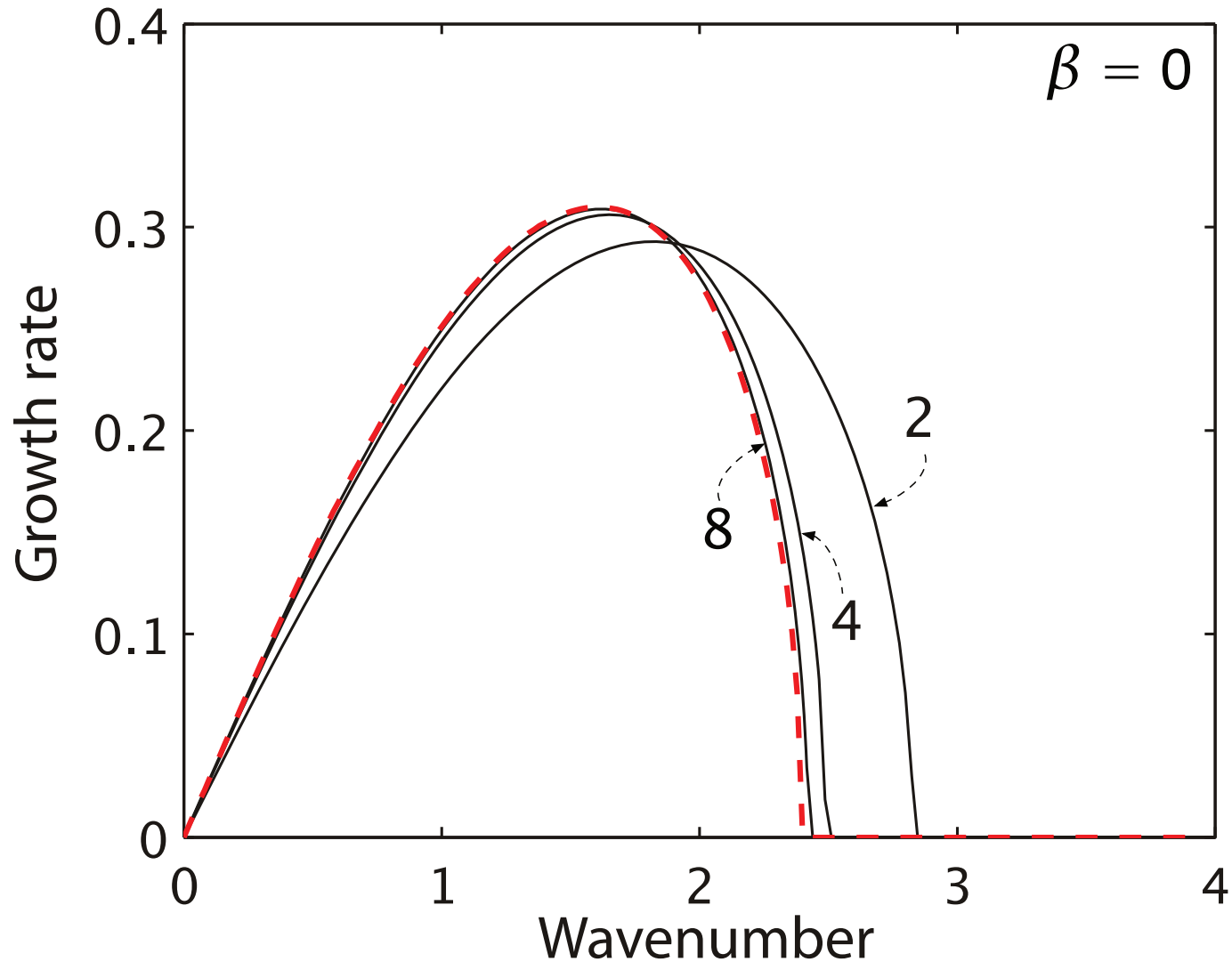
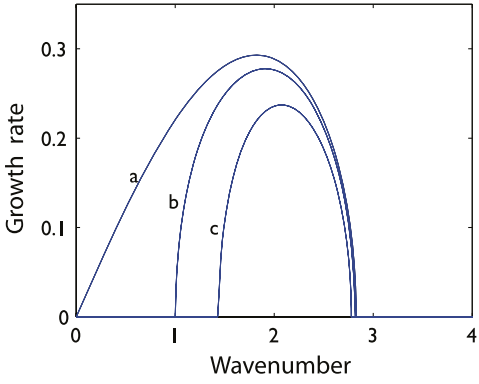


Fig. 9.13


Growth rate
0.3
0.2
0.1
0
a
b
c
0
1
2
3
4
Wavenumber

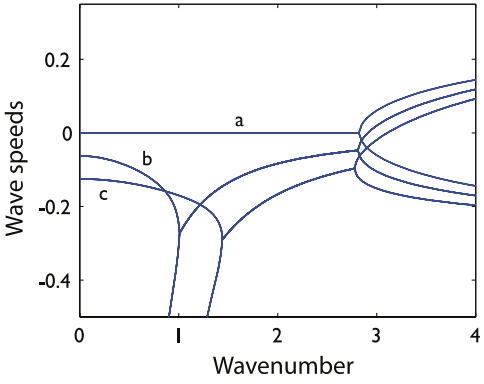

Wave speeds
0.2
0
-0.2
-0.4
a
b
c
0
1
2
3
4
Wavenumber

Fig. 9.14

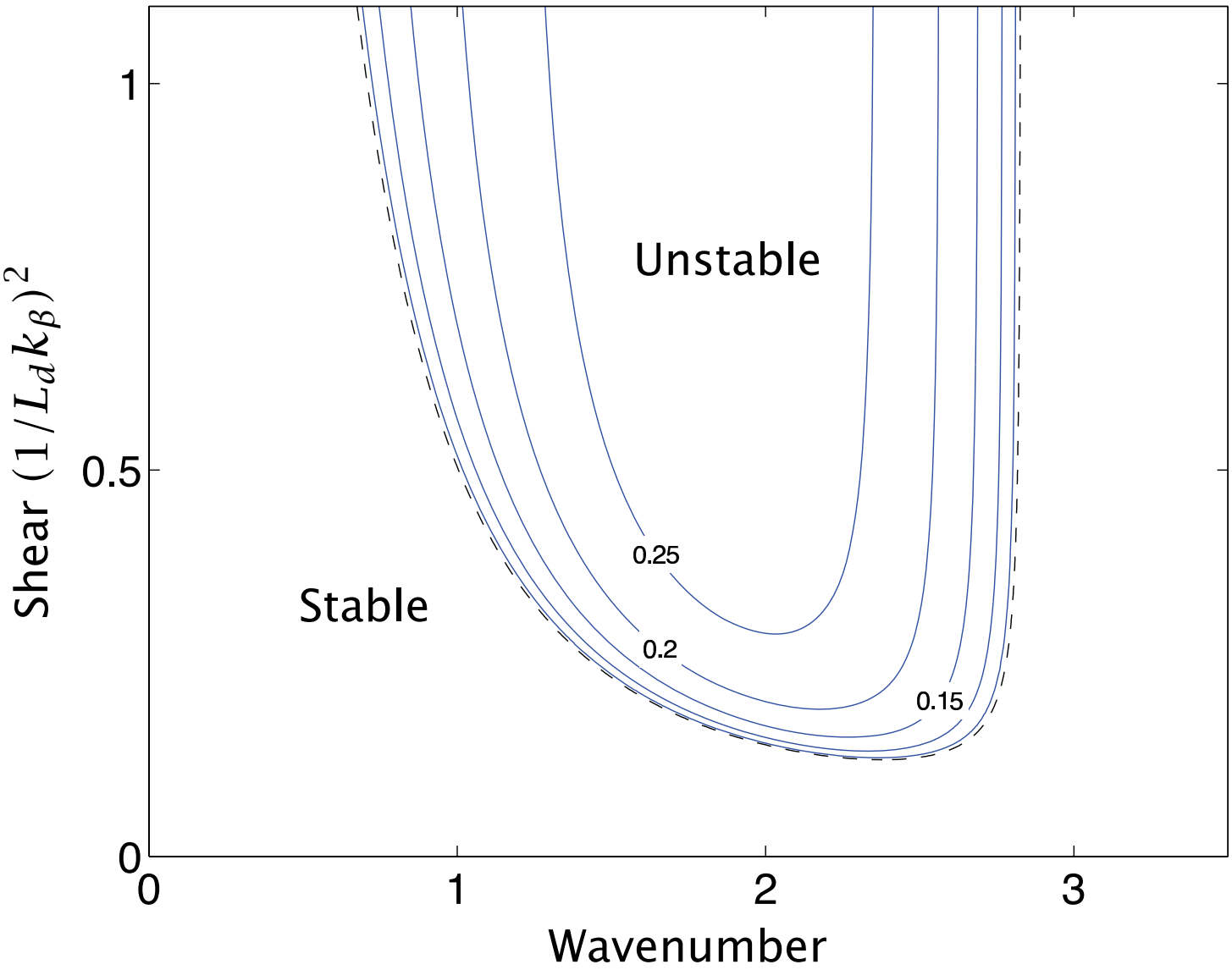
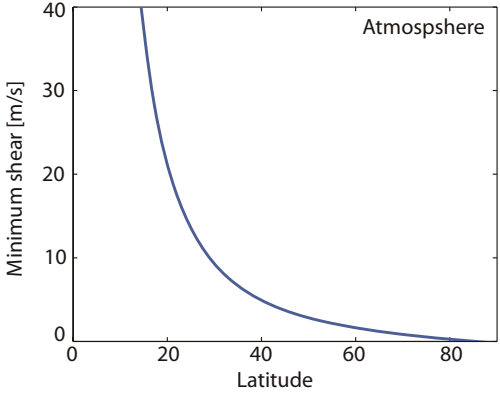

Unstable
Stable
0.25
0.2
0.15
Shear $(1/L_d k_\beta)^2$
Wavenumber
0
0.5
1
0
1
2
3

Fig. 9.15


Atmospsphere
Minimum shear [m/s]
Latitude
0
10
20
30
40
0
20
40
60
80

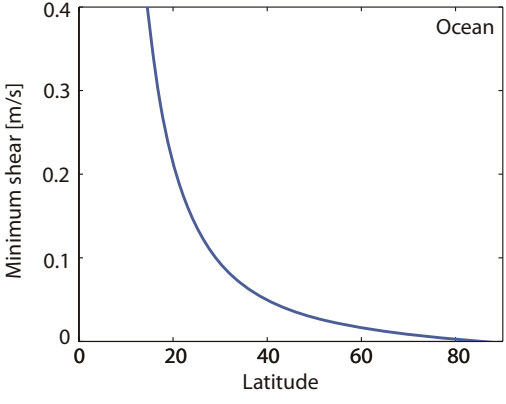

Ocean
Minimum shear [m/s]
Latitude
0
0.1
0.2
0.3
0.4
0
20
40
60
80

Fig. 9.16

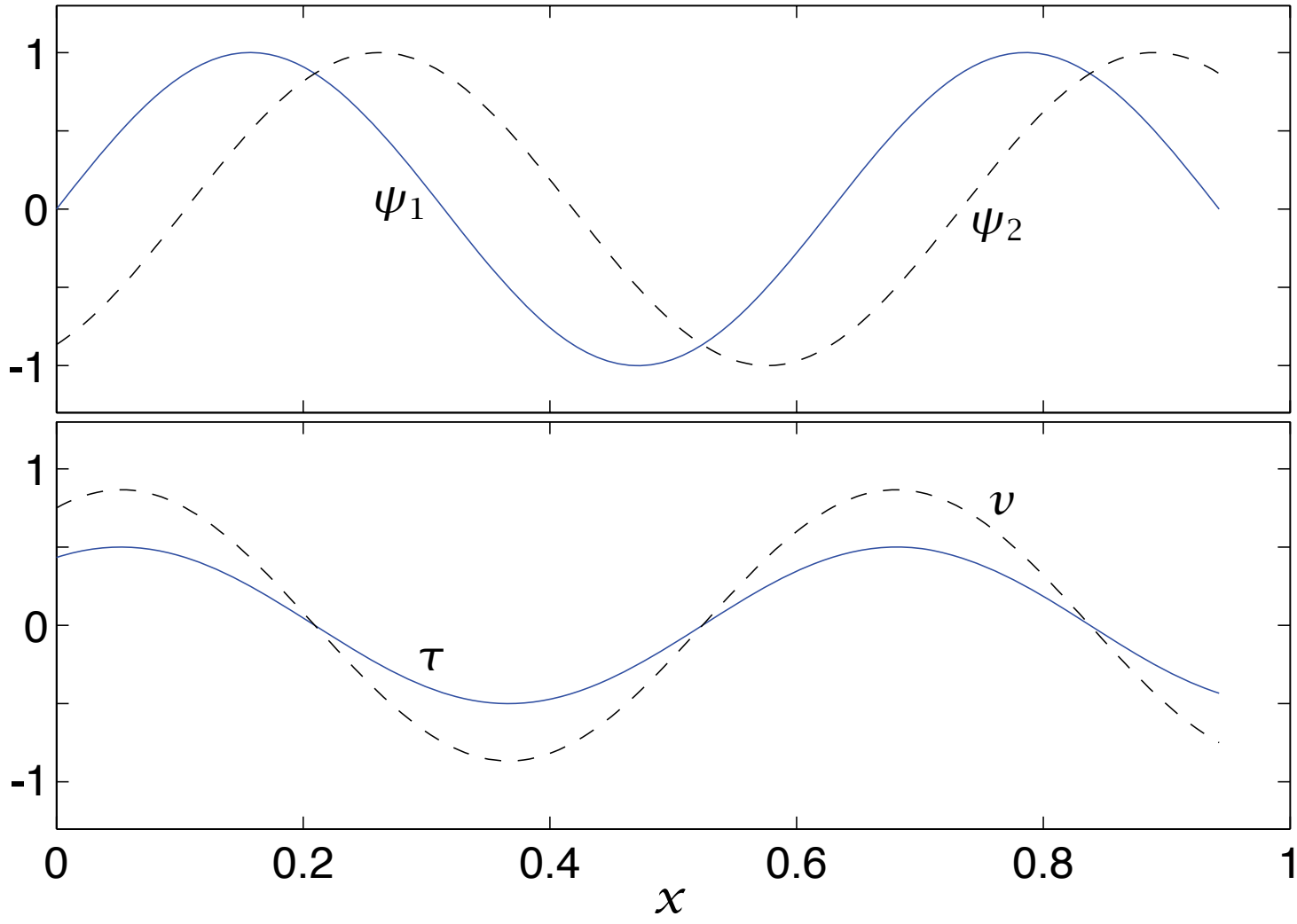


Fig. 9.17

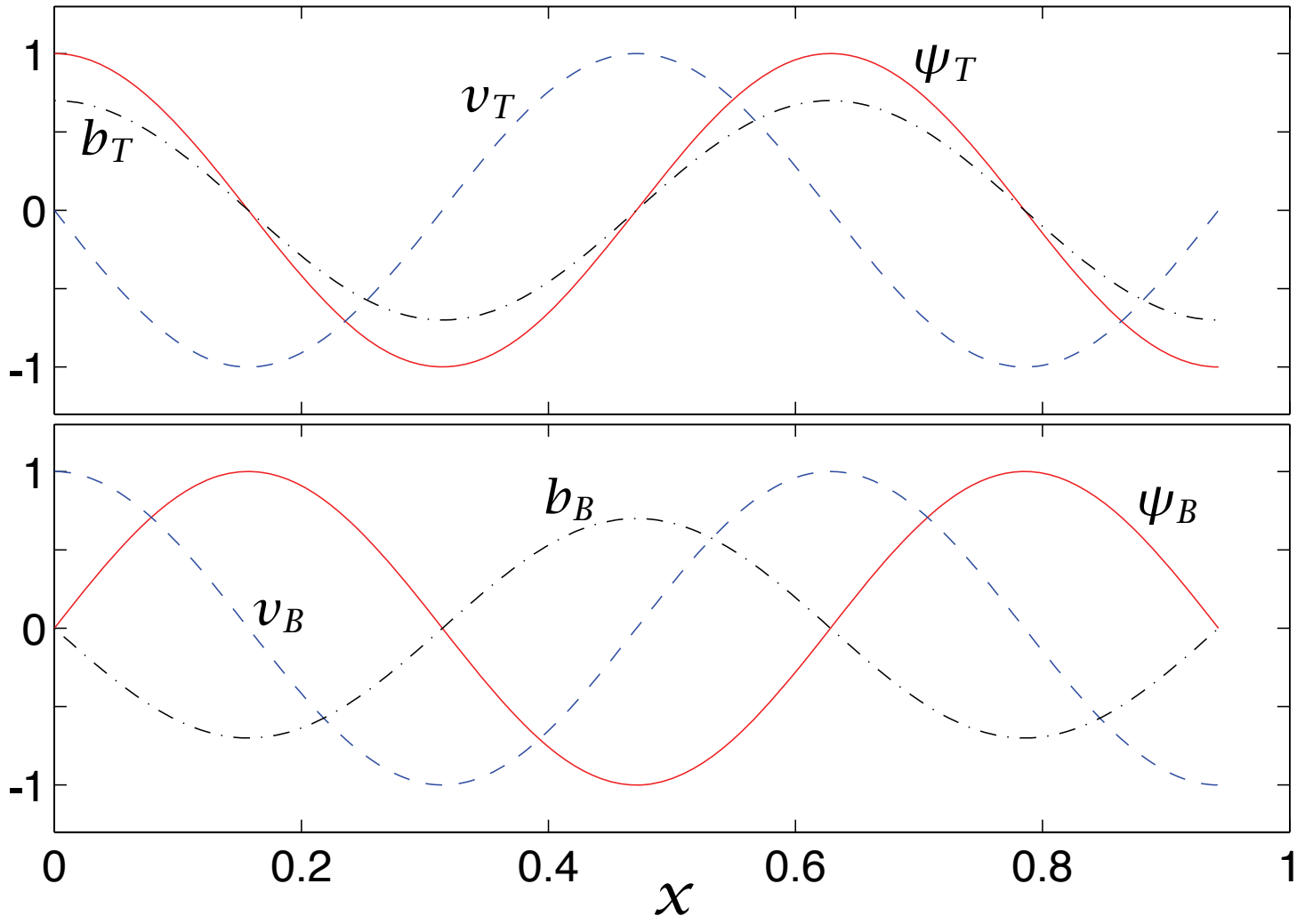
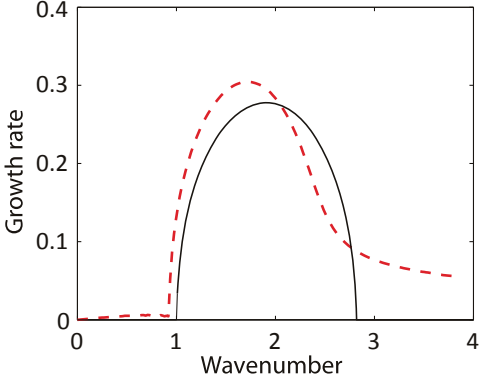


Fig. 9.18


0.4
0.3
0.2
0.1
0
Growth rate
0
1
2
3
4
Wavenumber

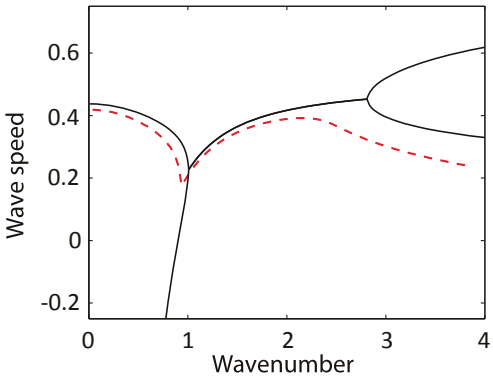
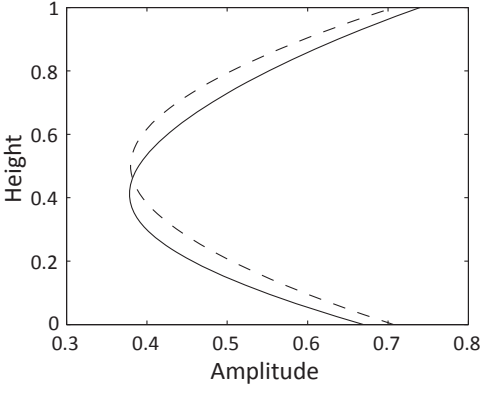

0.6
0.4
0.2
0
-0.2
Wave speed
0
1
2
3
4
Wavenumber

Fig. 9.19


Height
Amplitude
0
0.2
0.4
0.6
0.8
1
0.3
0.4
0.5
0.6
0.7
0.8

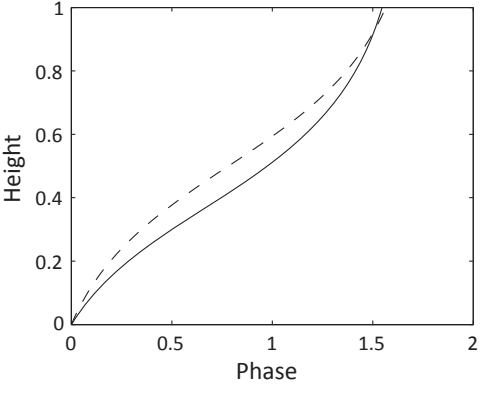

Height
Phase
0
0.2
0.4
0.6
0.8
1
0
0.5
1
1.5
2

Fig. 9.20

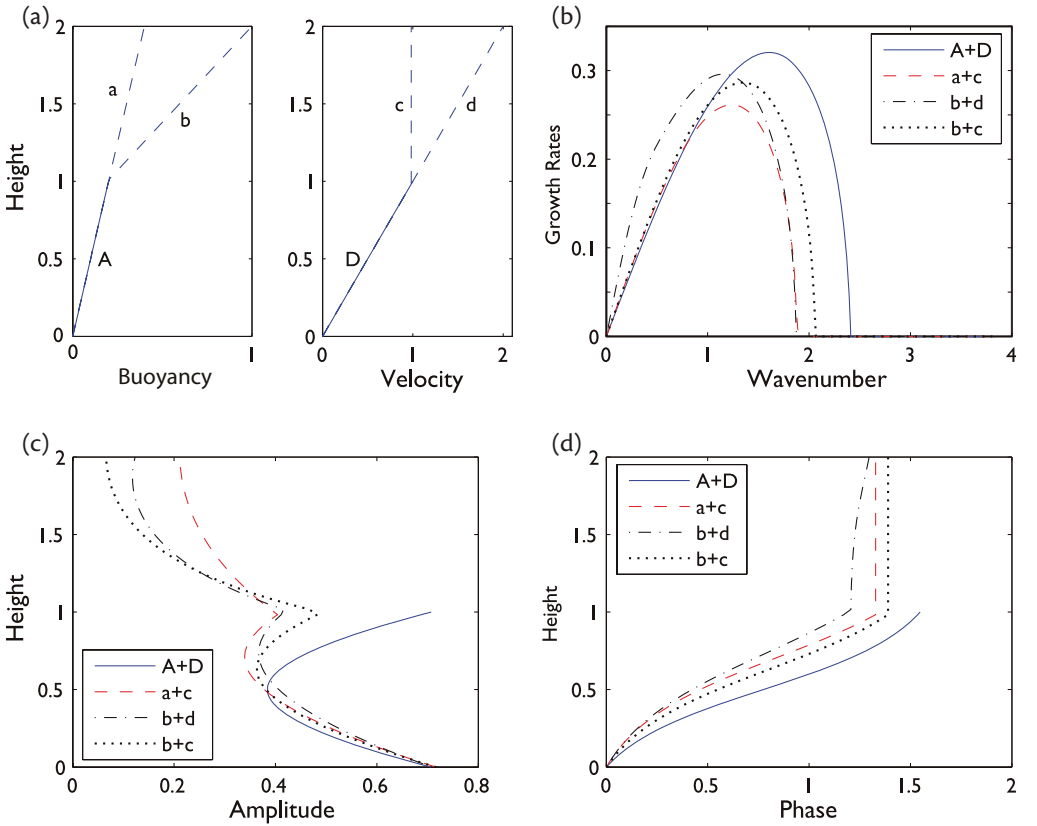

(a)
Height
Buoyancy
Velocity
A
a
b
D
c
d
(b)
Growth Rates
Wavenumber
A+D
a+c
b+d
b+c
(c)
Height
Amplitude
A+D
a+c
b+d
b+c
(d)
Height
Phase
A+D
a+c
b+d
b+c

Fig. 9.21

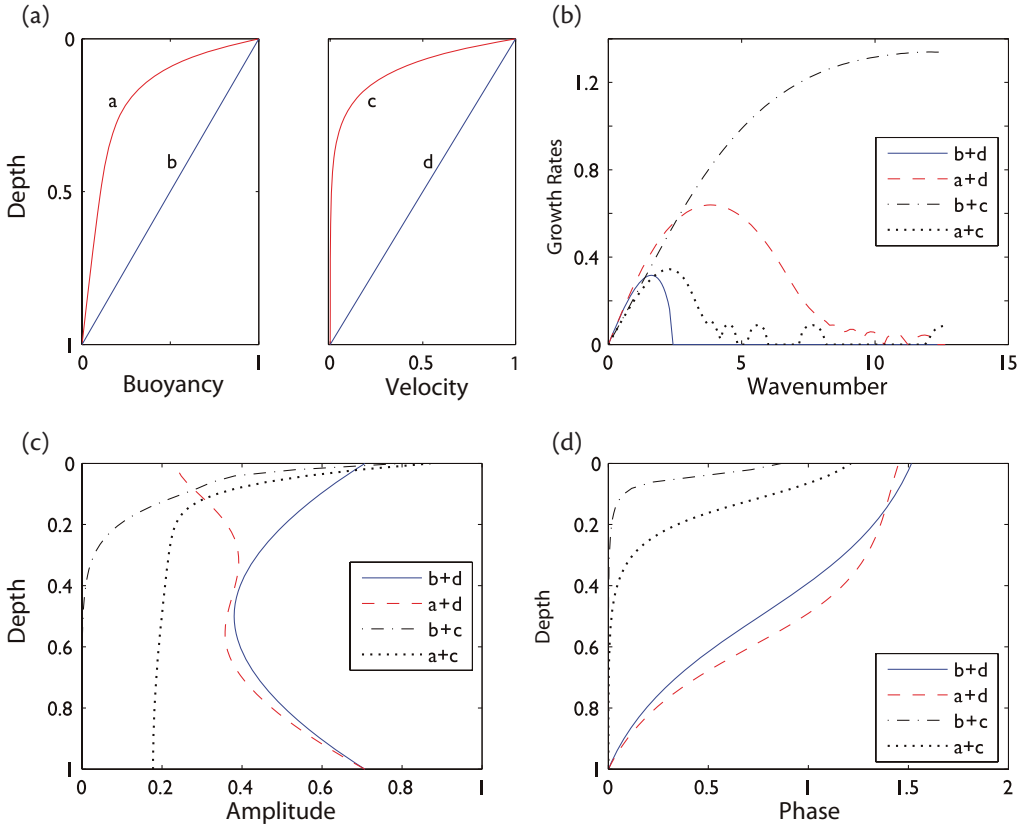

(a)
Depth
Buoyancy
Velocity
a
b
c
d
(b)
Growth Rates
Wavenumber
b+d
a+d
b+c
a+c
(c)
Depth
Amplitude
(d)
Depth
Phase

Fig. 9.22

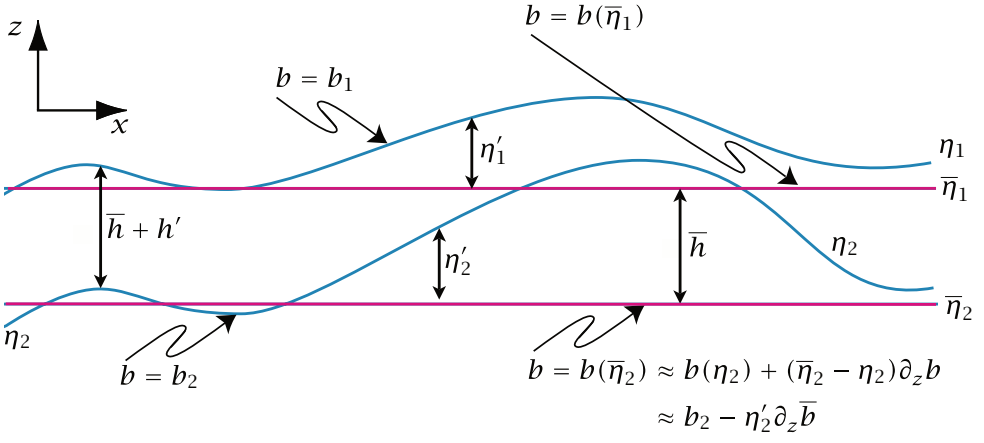

z
x
$b = b(\overline{\eta}_1)$
$b = b_1$
η_1'
η_1
$\overline{\eta}_1$
$\overline{h} + h'$
η_2'
$\overline{h}$
η_2
$\overline{\eta}_2$
η_2
$b = b_2$
$b = b(\overline{\eta}_2) \approx b(\eta_2) + (\overline{\eta}_2 - \eta_2)\partial_z b$
$\approx b_2 - \eta_2' \partial_z \overline{b}$

Fig. 10.1

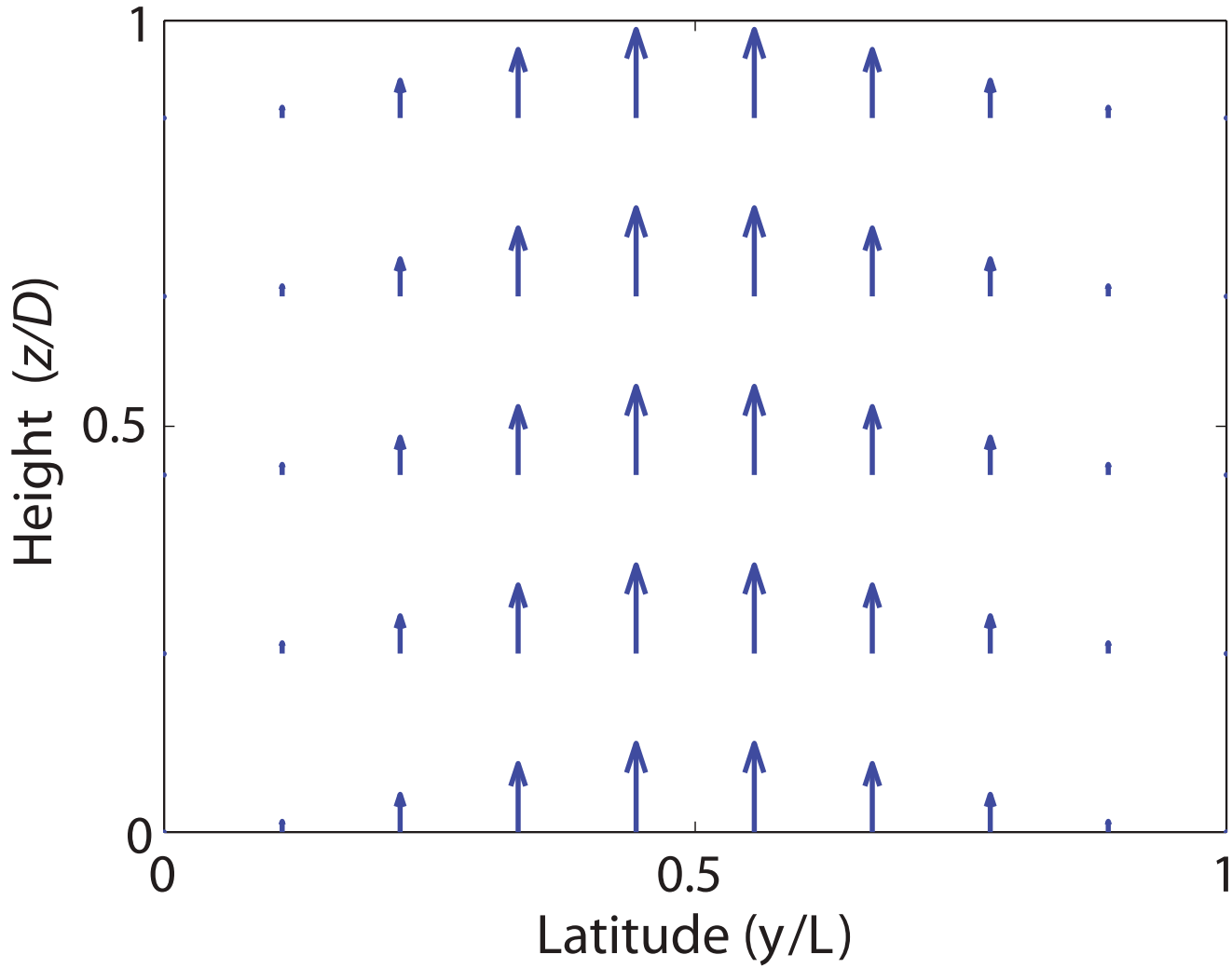


Fig. 10.2

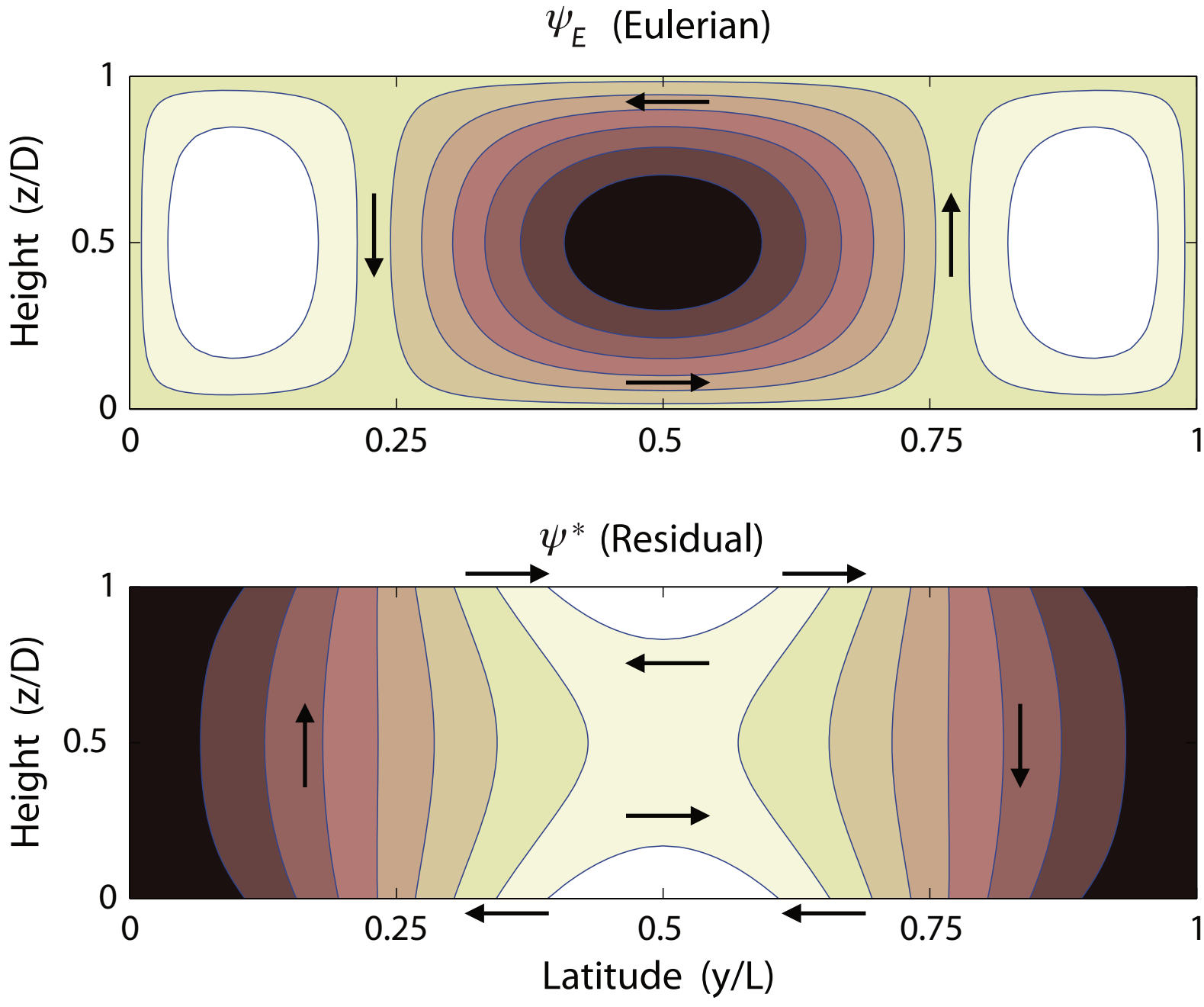

ψ_E (Eulerian)
Height (z/D)
1
0.5
0
0
0.25
0.5
0.75
1
ψ^* (Residual)
Height (z/D)
1
0.5
0
0
0.25
0.5
0.75
1
Latitude (y/L)

Fig. 10.3

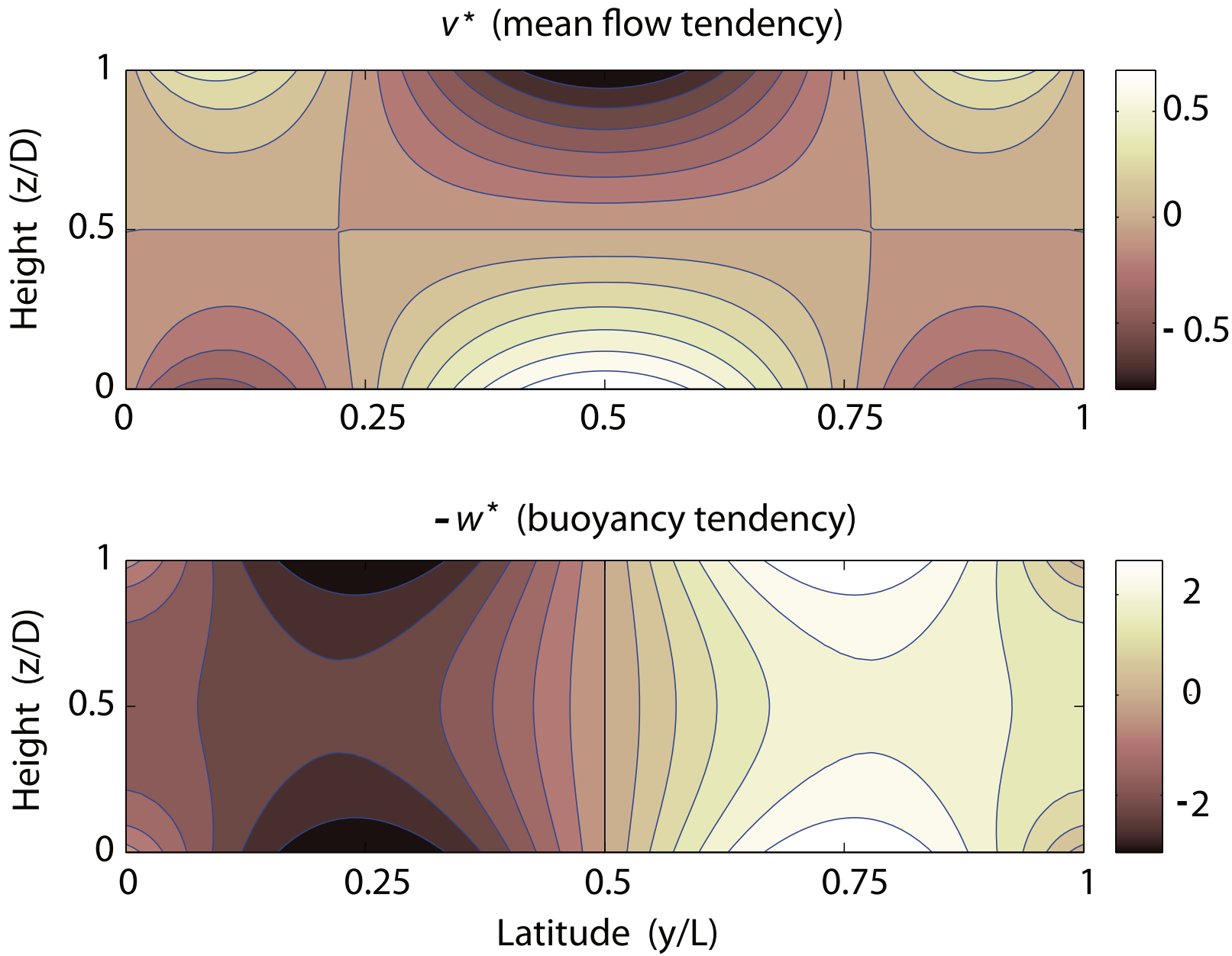

v* (mean flow tendency)
Height (z/D)
1
0.5
0
0
0.25
0.5
0.75
1
0.5
0
- 0.5
-w* (buoyancy tendency)
Height (z/D)
1
0.5
0
0
0.25
0.5
0.75
1
2
0
-2
Latitude (y/L)

Fig. 10.4

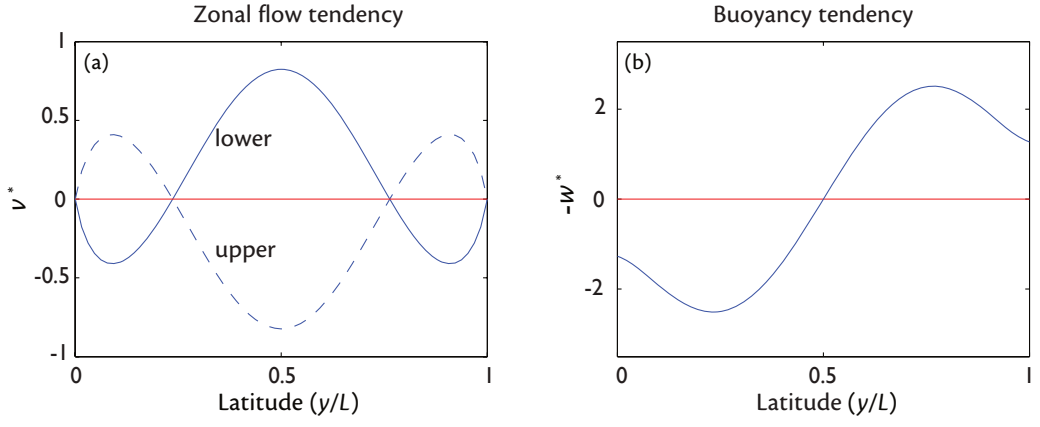

Zonal flow tendency
(a)
lower
upper
v^*
1
0.5
0
-0.5
-1
0
0.5
1
Latitude (y/L)
Buoyancy tendency
(b)
$-w^*$
2
0
-2
0
0.5
1
Latitude (y/L)

Fig. 10.5

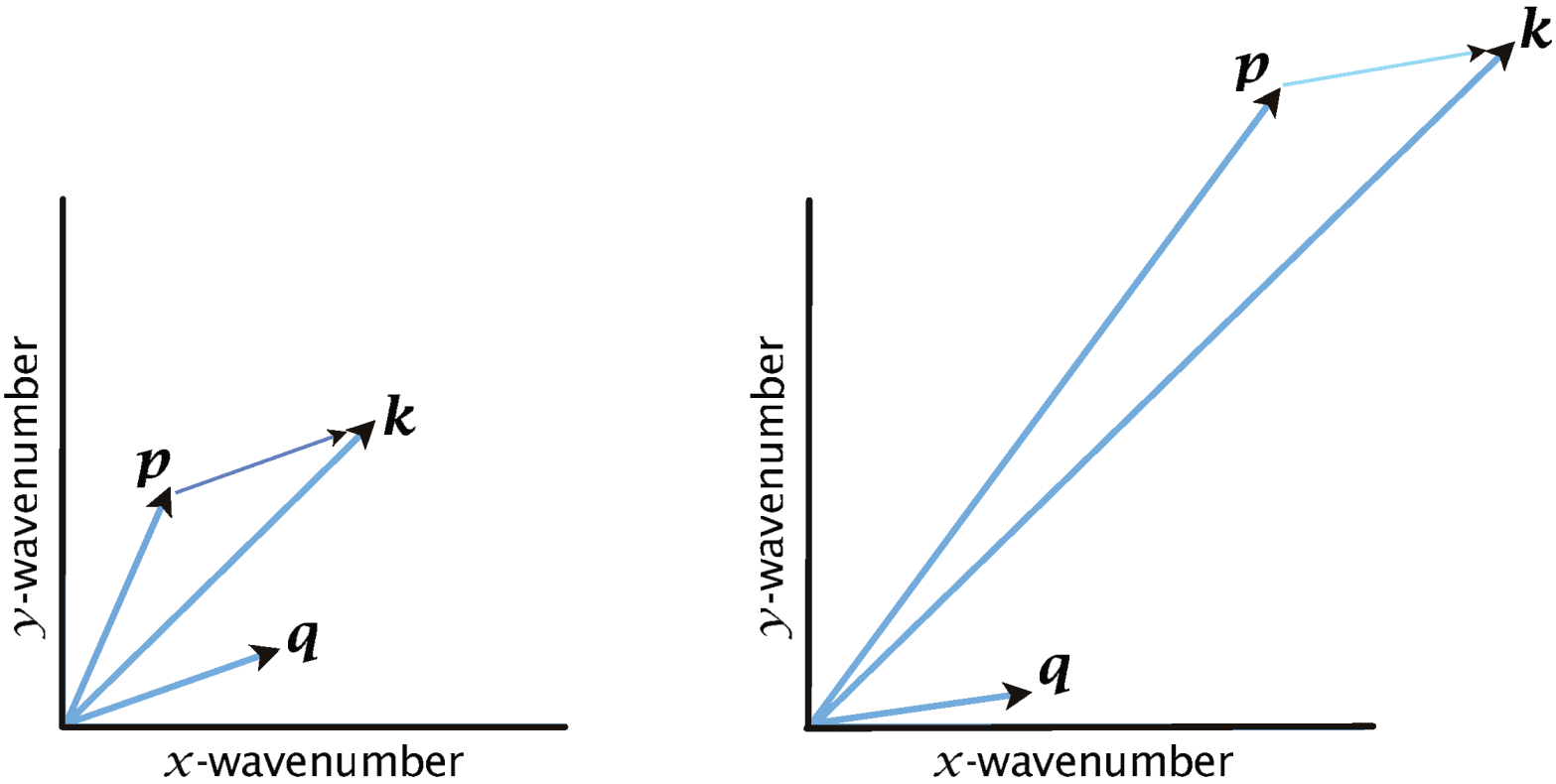

y-wavenumber
x-wavenumber
p
k
q
y-wavenumber
x-wavenumber
p
k
q

Fig. 11.1

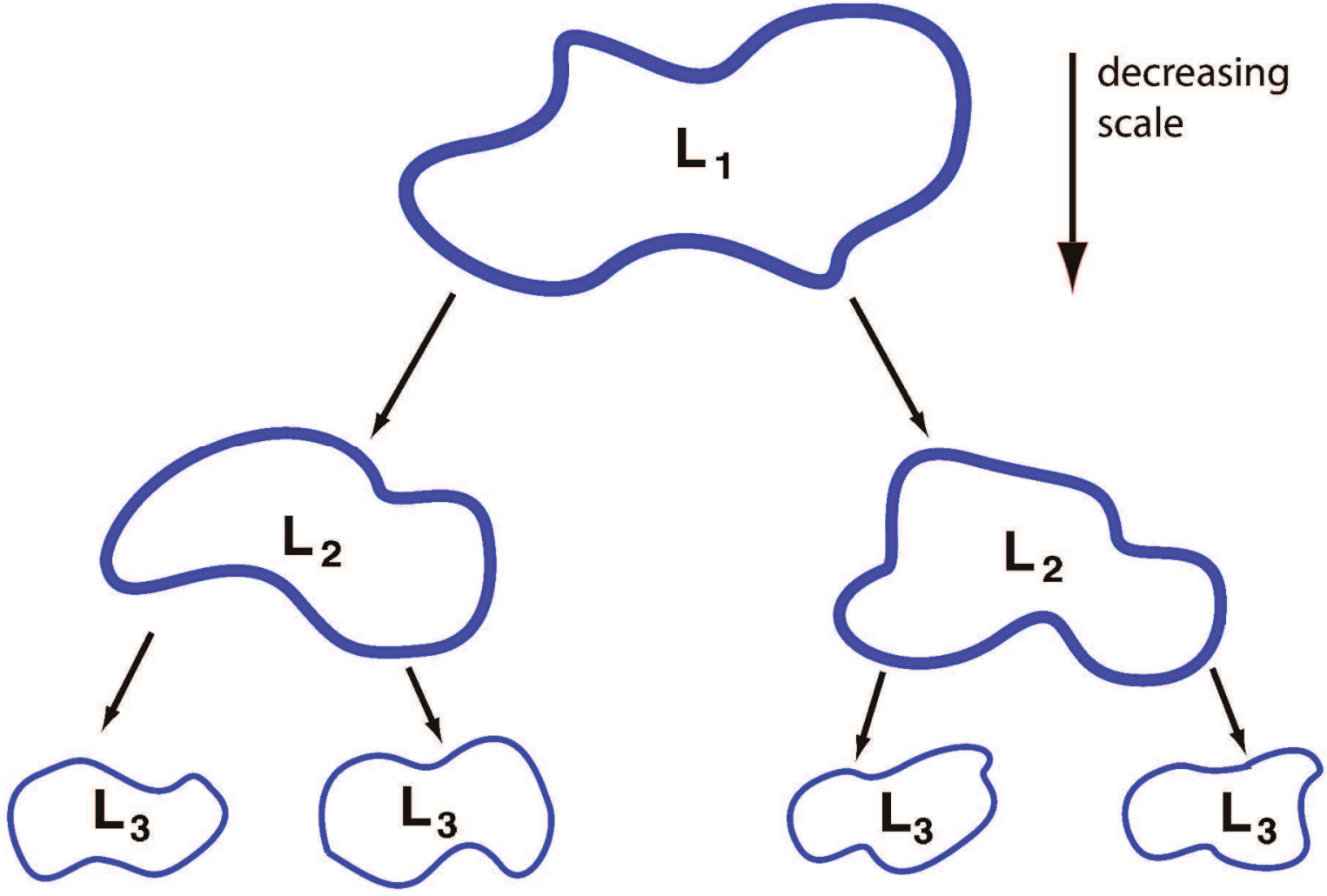


Fig. 11.2

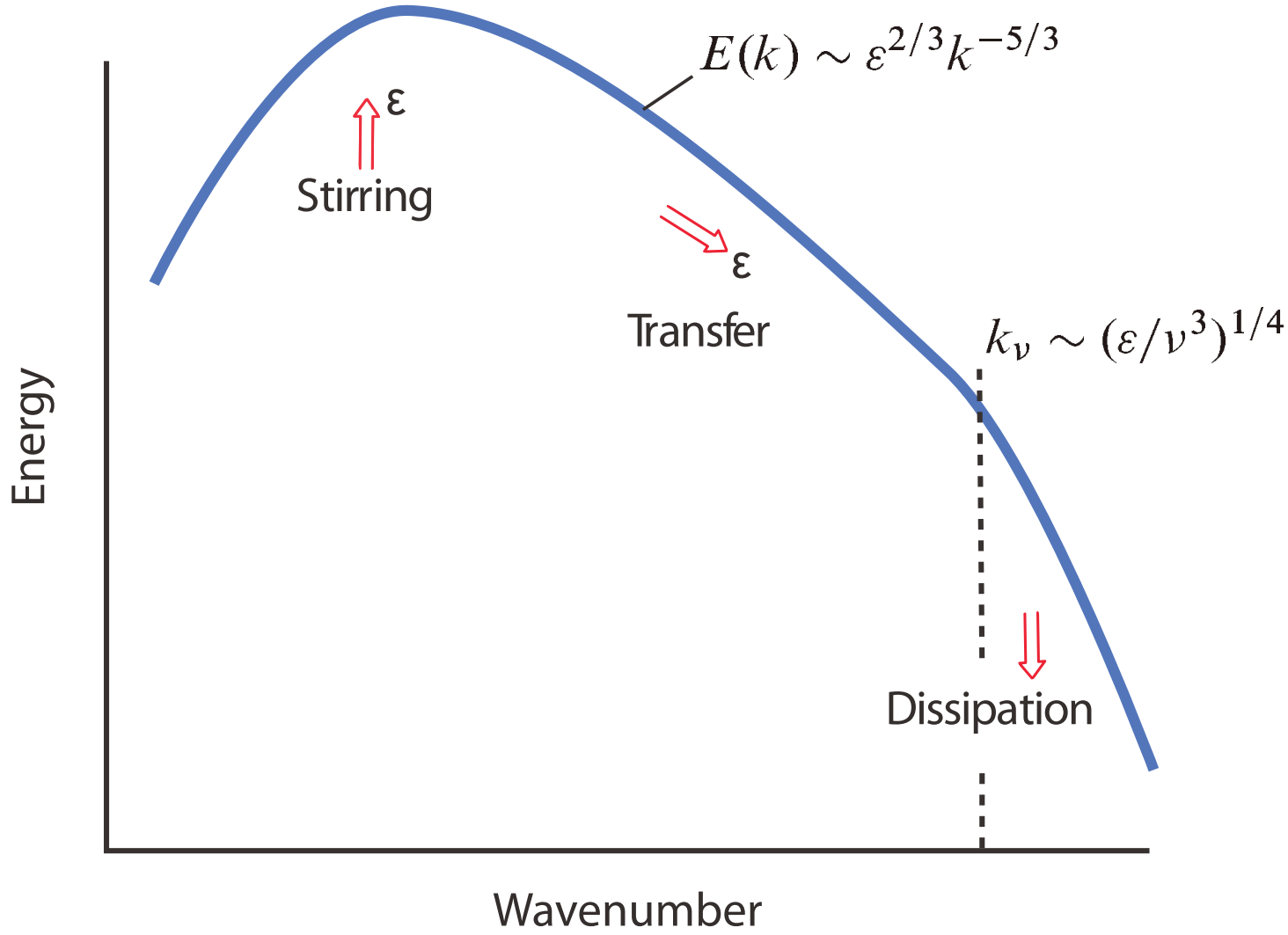

$E(k) \sim \varepsilon^{2/3} k^{-5/3}$
ε
Stirring
ε
Transfer
$k_v \sim (\varepsilon/\nu^3)^{1/4}$
Dissipation
Energy
Wavenumber

Fig. 11.3

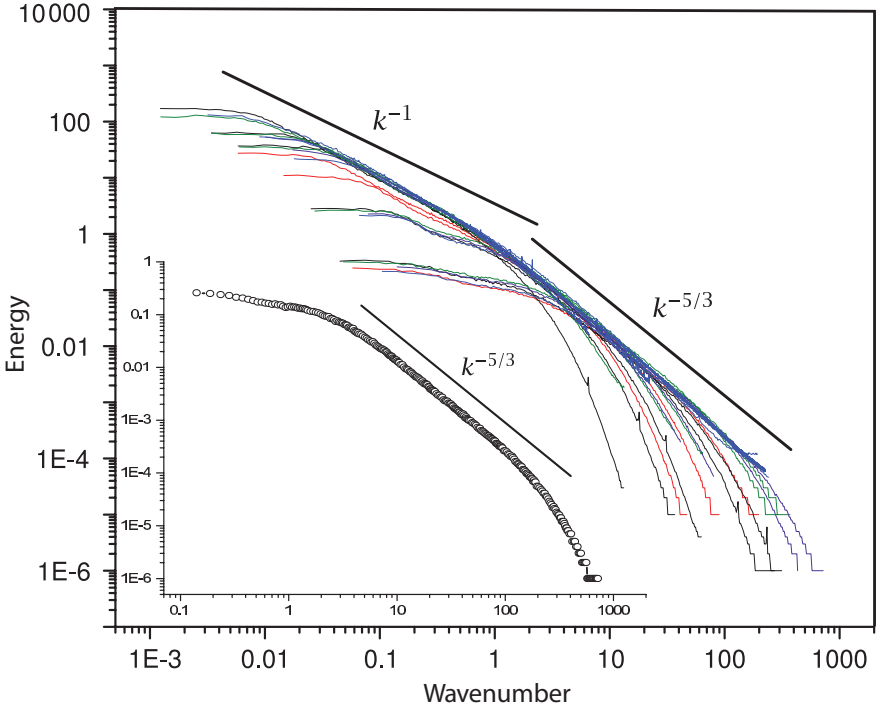

10000
100
1
0.01
1E-4
1E-6
Energy
1E-3
0.01
0.1
1
10
100
1000
Wavenumber
k^{-1}
$k^{-5/3}$
$k^{-5/3}$
1
0.1
0.01
1E-3
1E-4
1E-5
1E-6
0.1
1
10
100
1000

Fig. 11.4

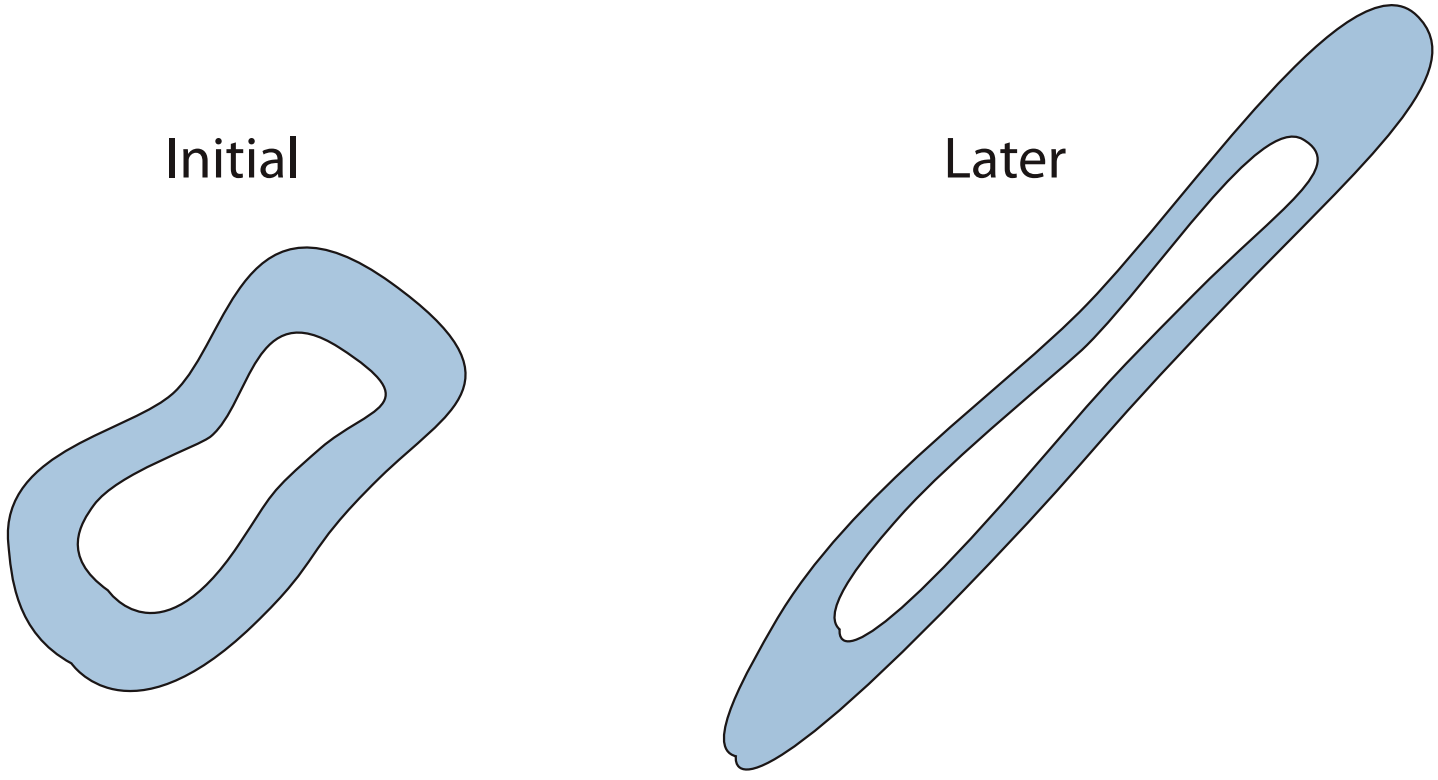


Fig. 11.5

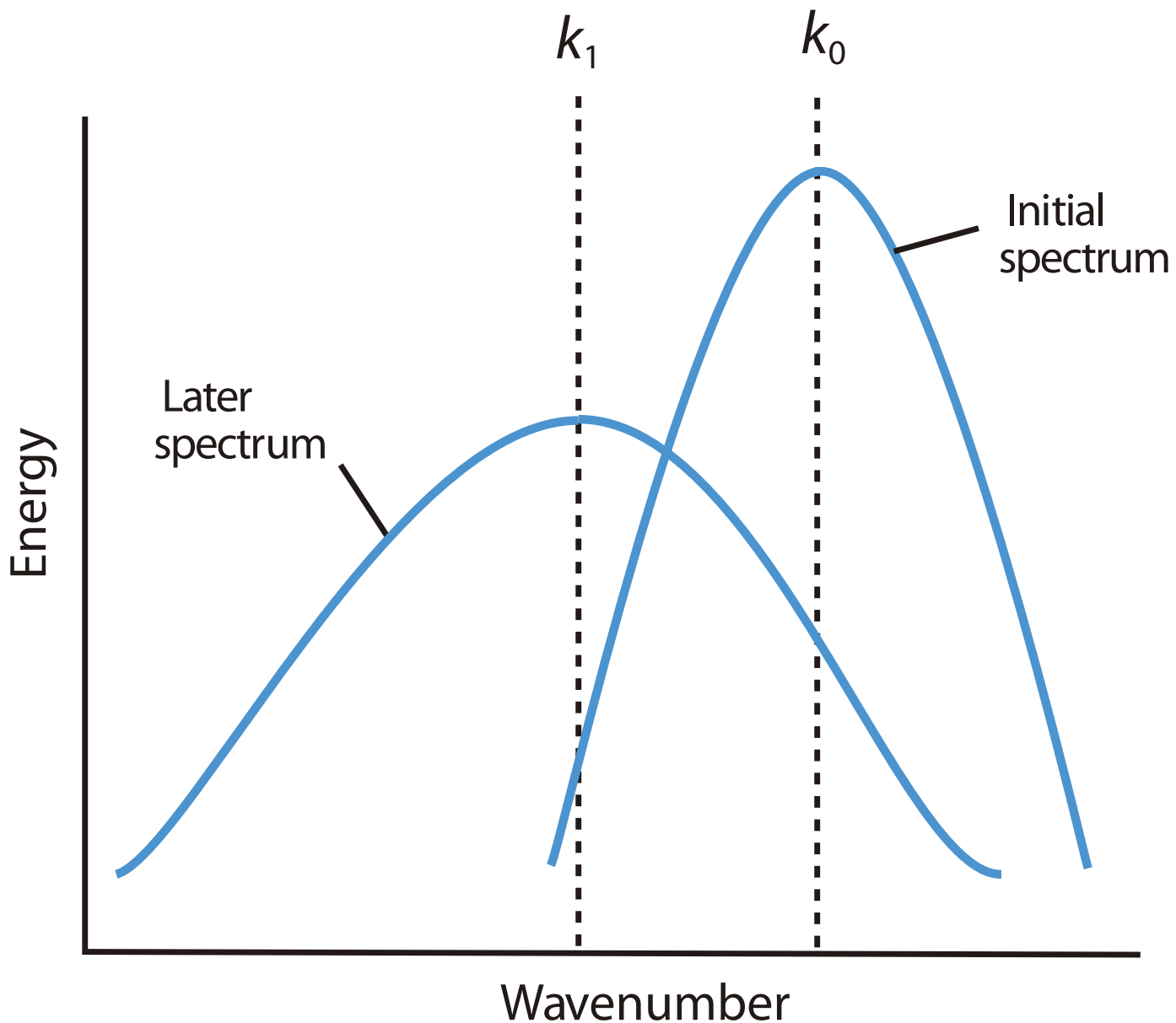


Fig. 11.6

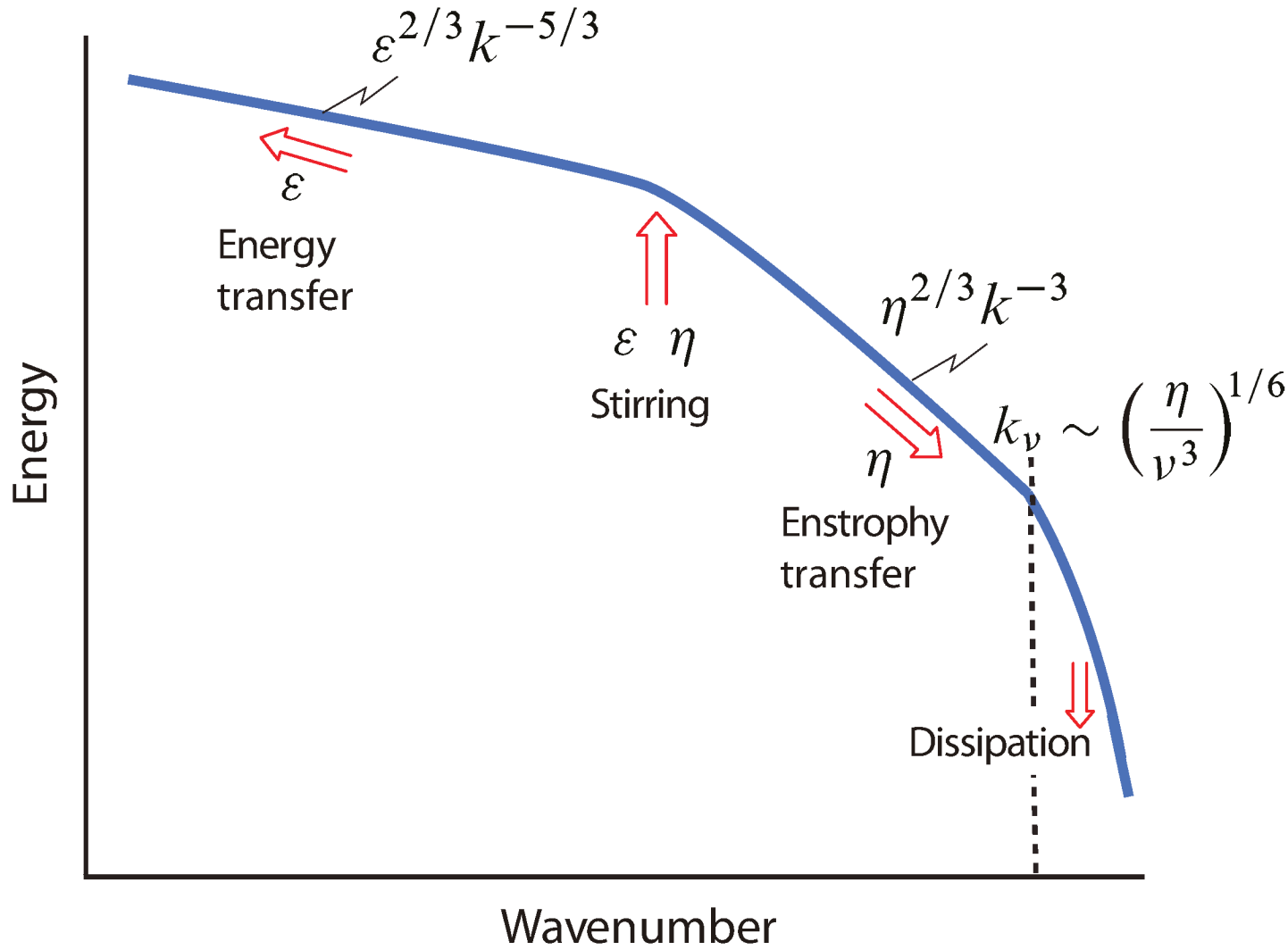

$\varepsilon^{2/3}k^{-5/3}$
ε
Energy
transfer
ε η
Stirring
$\eta^{2/3}k^{-3}$
η
Enstrophy
transfer
$k_\nu \sim \left(\frac{\eta}{\nu^3}\right)^{1/6}$
Dissipation
Energy
Wavenumber

Fig. 11.7

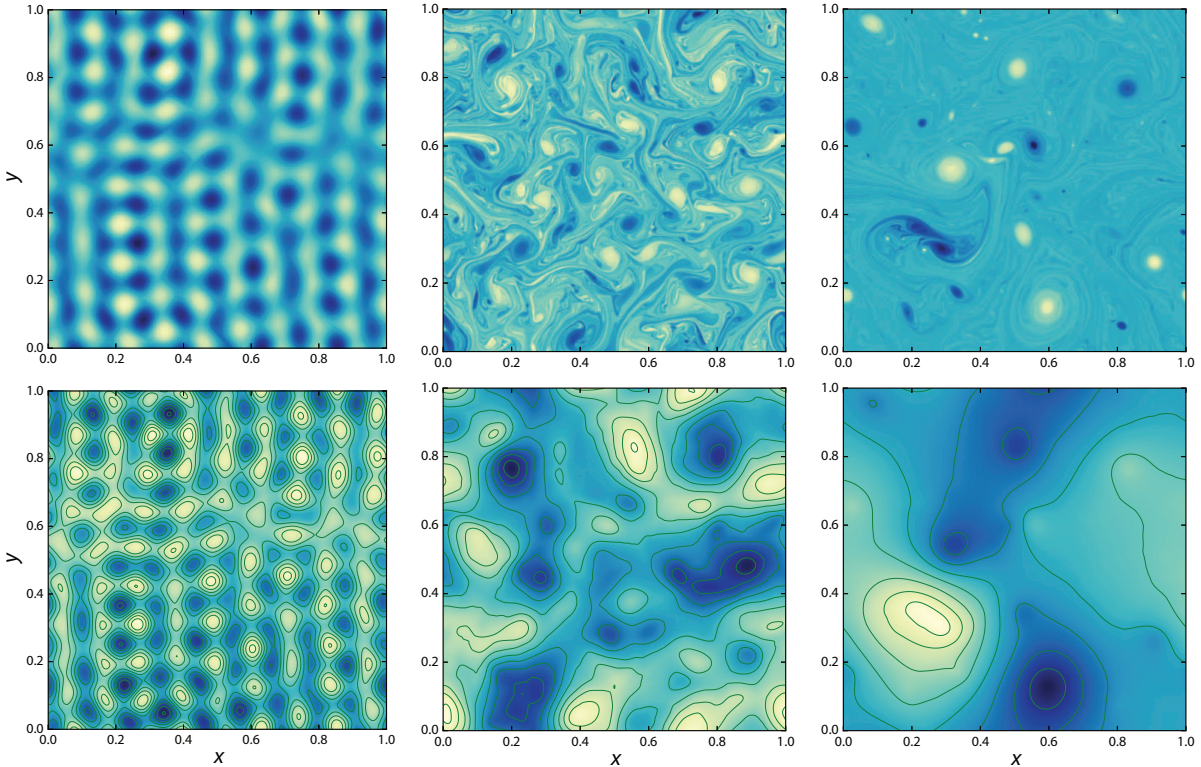


Fig. 11.8

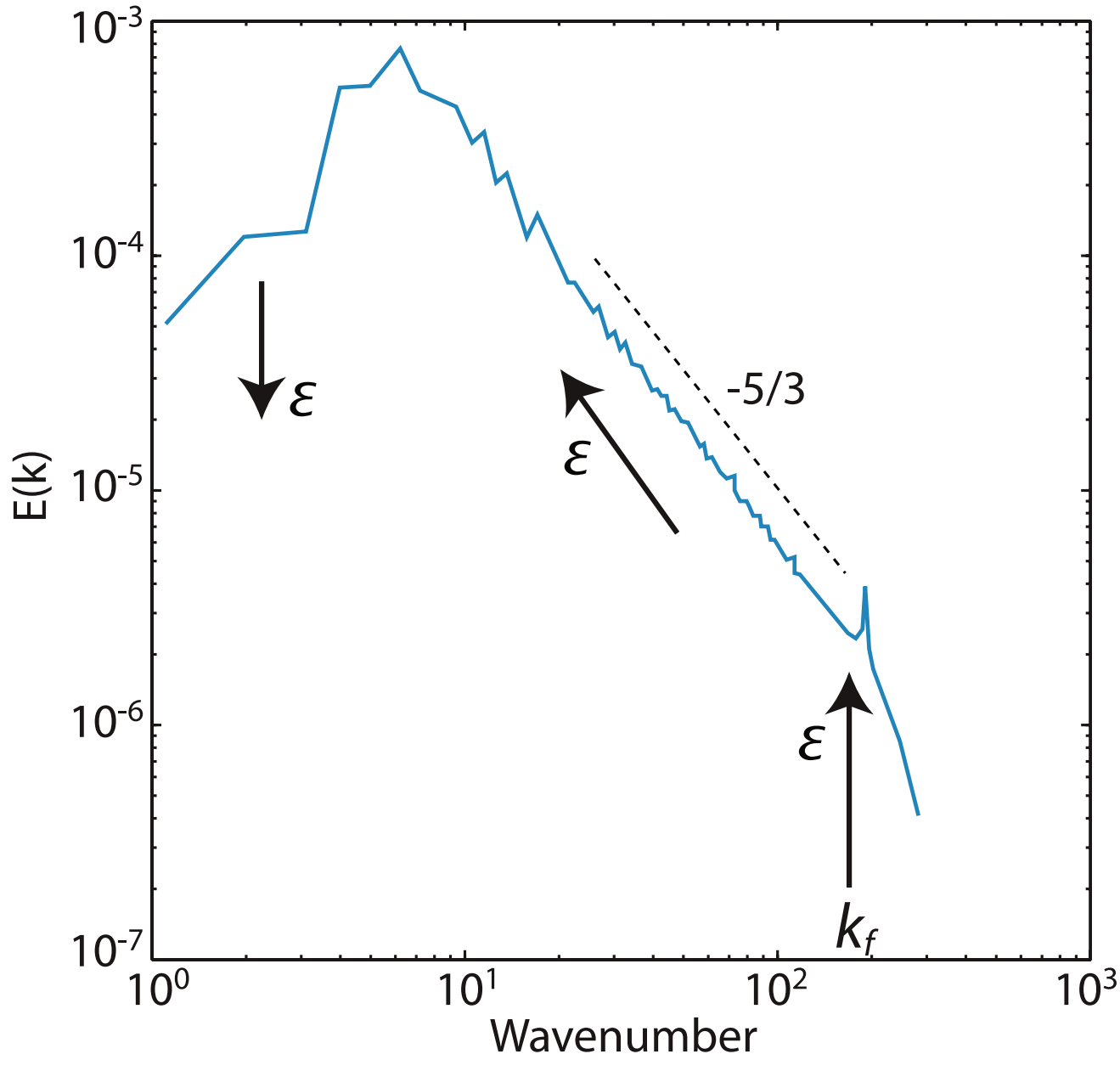


Fig. 11.9

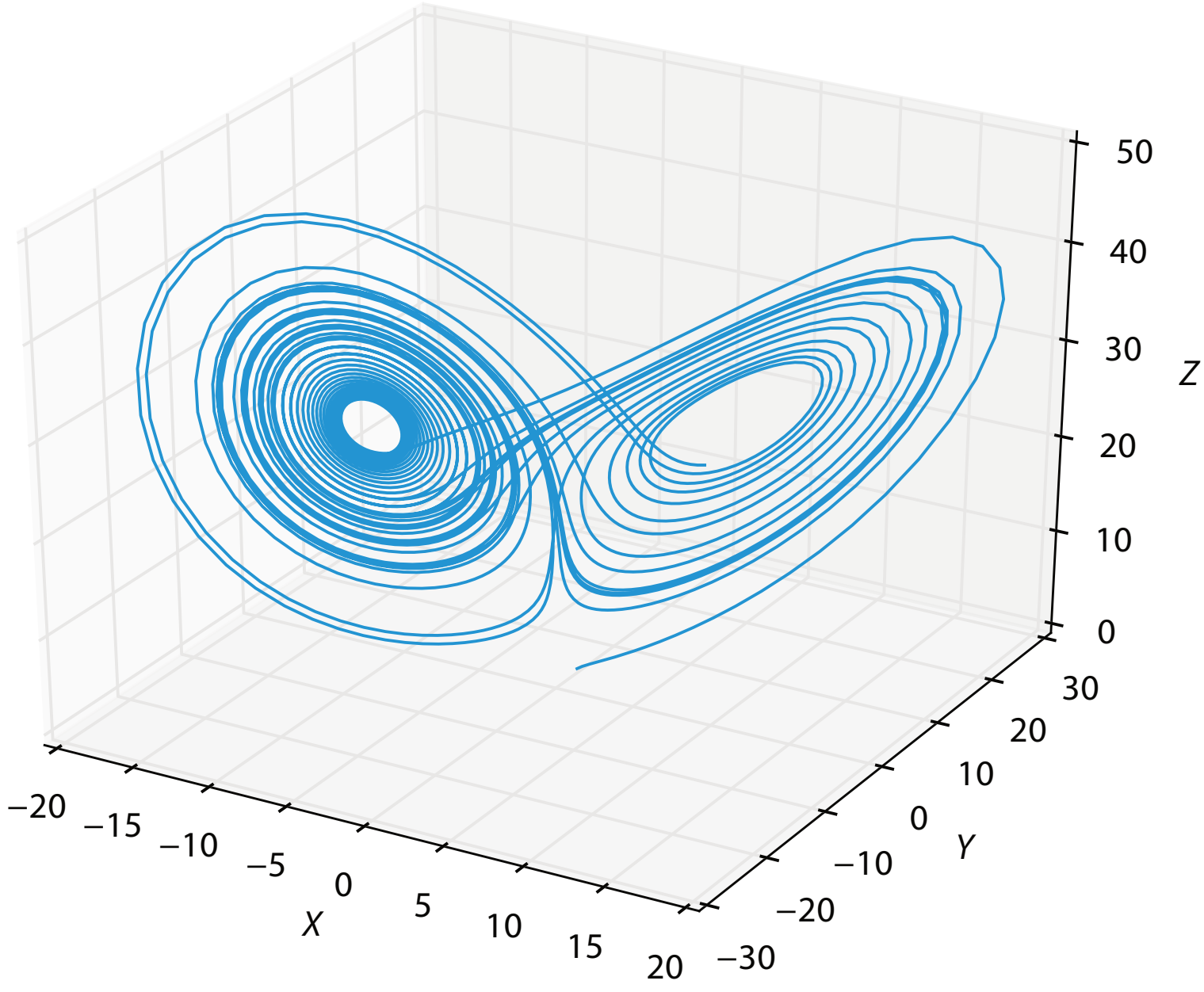
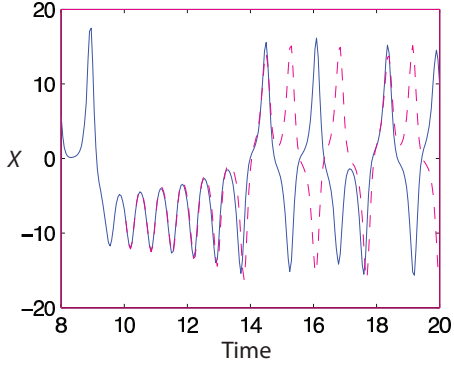


Fig. 11.10


20
10
X
0
−10
−20
8
10
12
14
16
18
20
Time

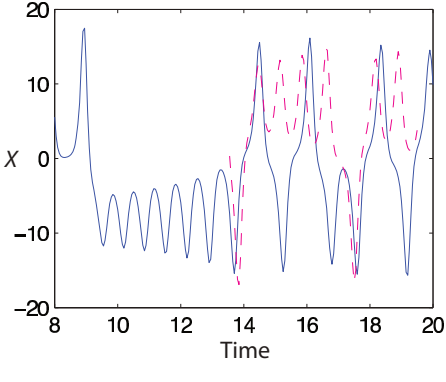

20
10
X
0
−10
−20
8
10
12
14
16
18
20
Time

Fig. 11.11

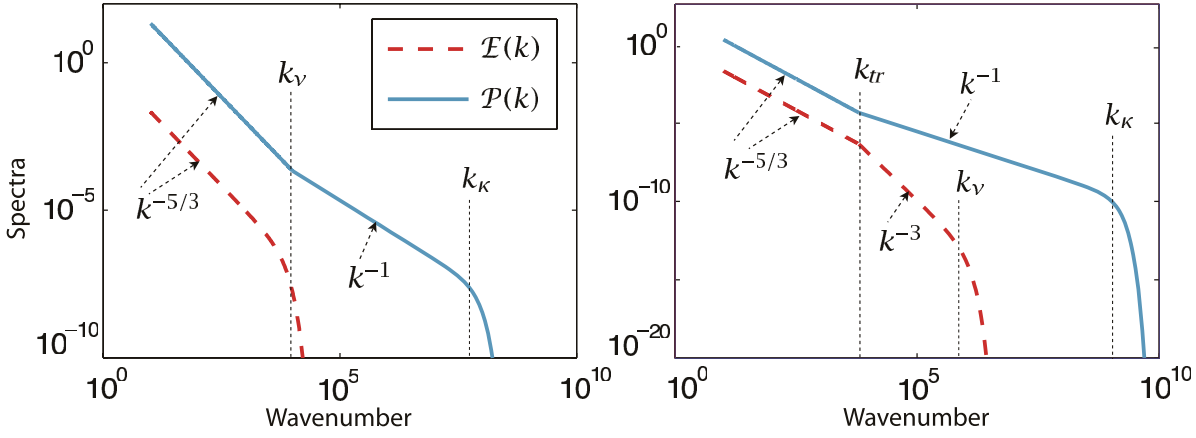

Spectra
Wavenumber
$\mathcal{E}(k)$
$\mathcal{P}(k)$
k_ν
k_κ
k_{tr}
$k^{-5/3}$
k^{-1}
k^{-3}
10^0
10^{-5}
10^{-10}
10^{-20}
10^5
10^{10}

Fig. 11.12

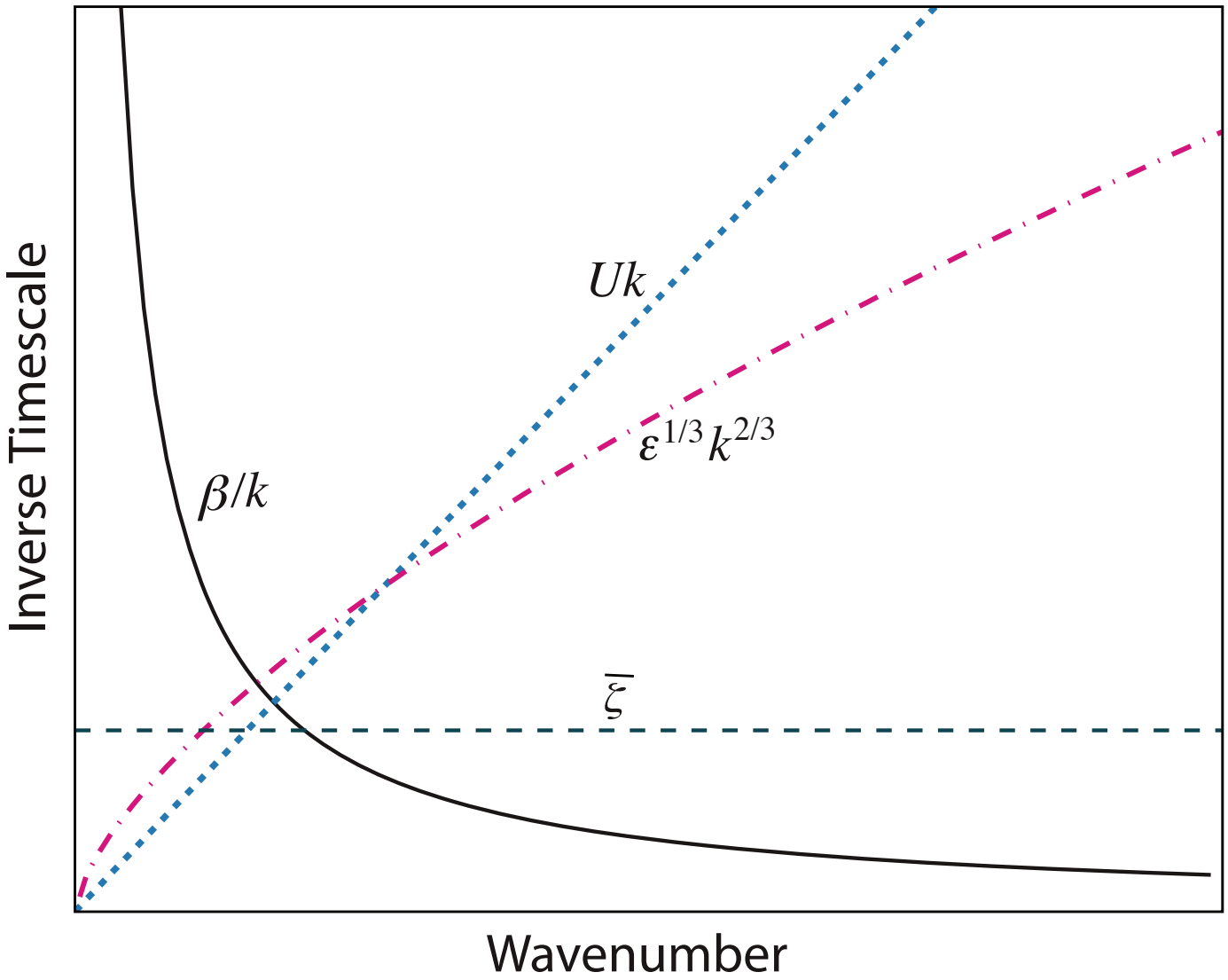

Inverse Timescale
Wavenumber
Uk
$\varepsilon^{1/3}k^{2/3}$
β/k
$\overline{\zeta}$

Fig. 12.1

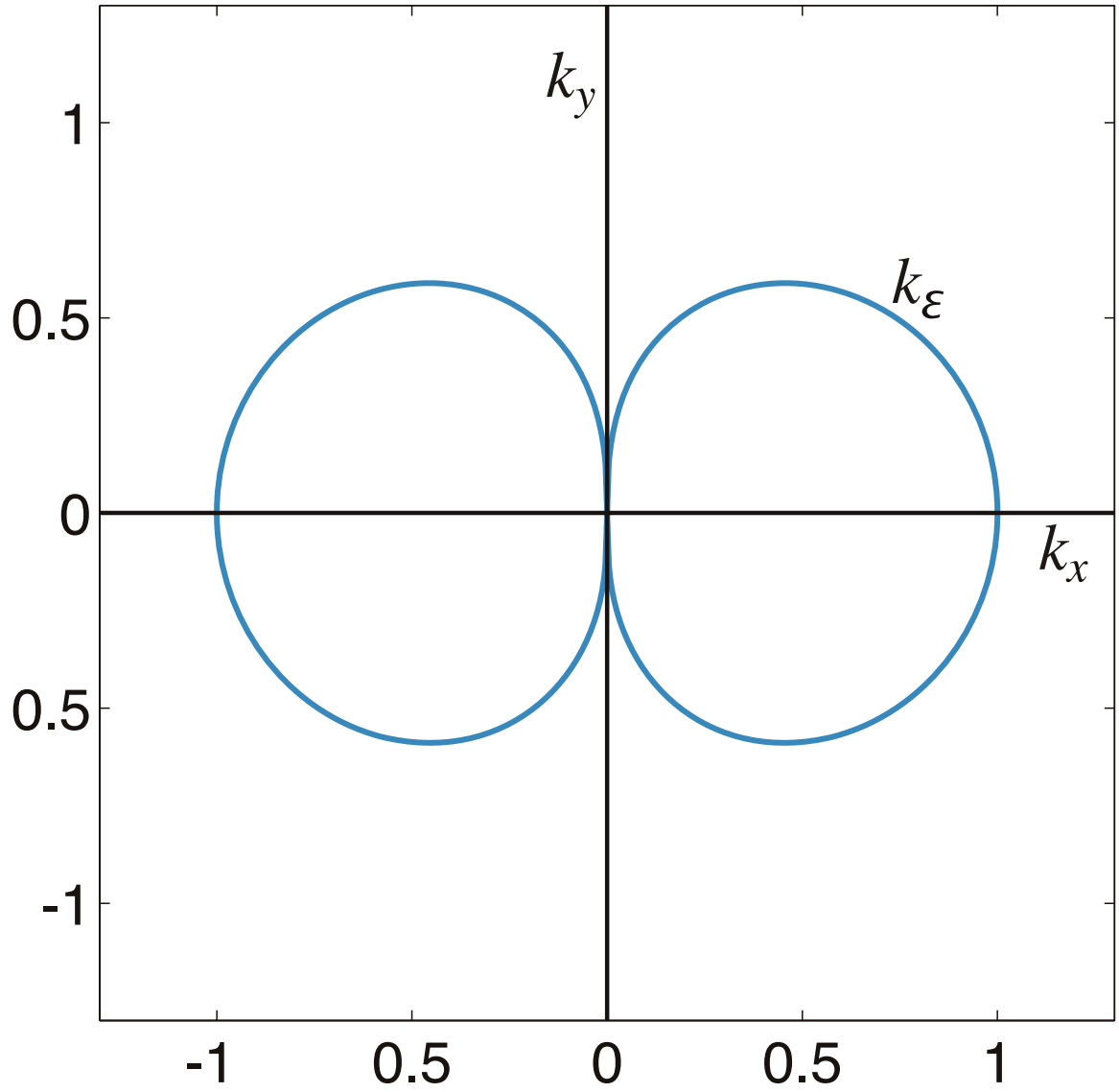


Fig. 12.2

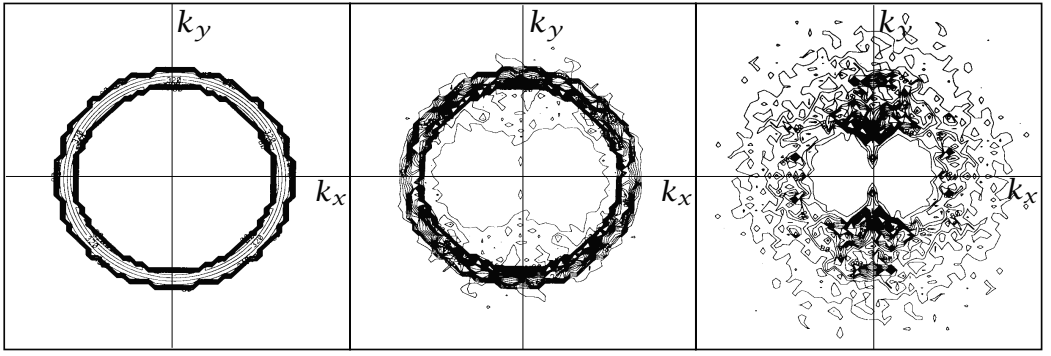


Fig. 12.3

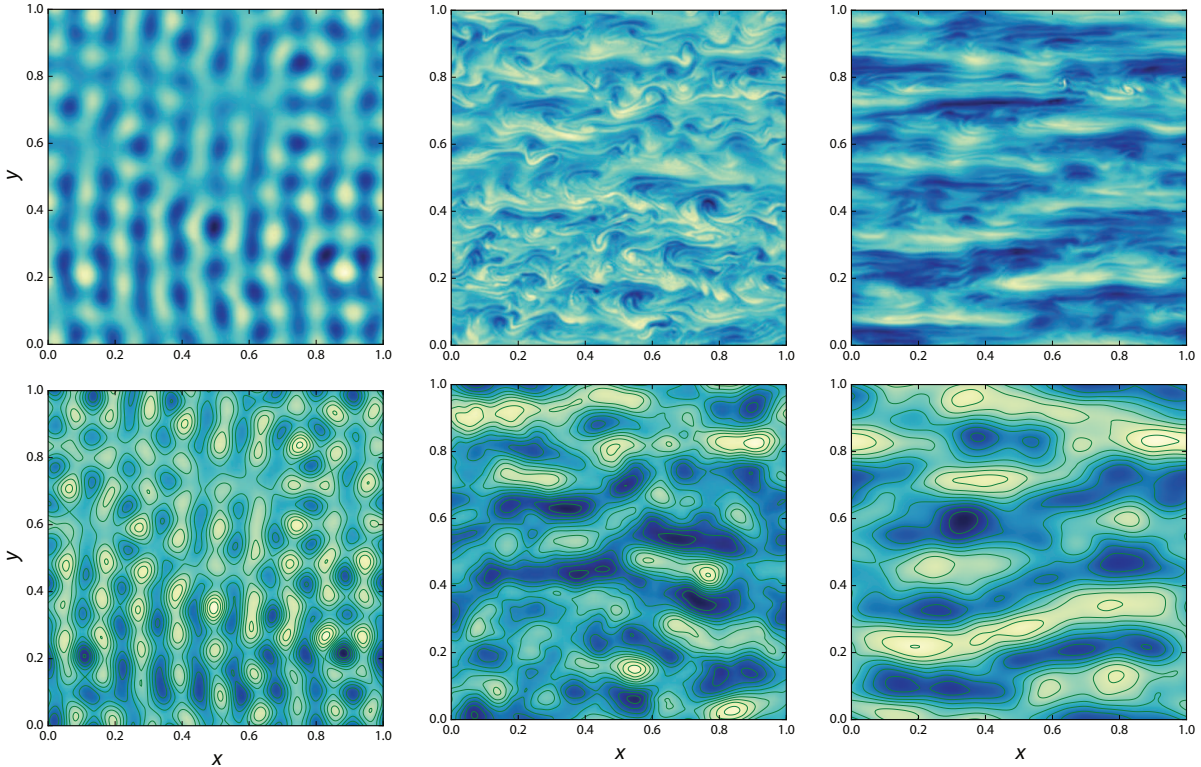


Fig. 12.4

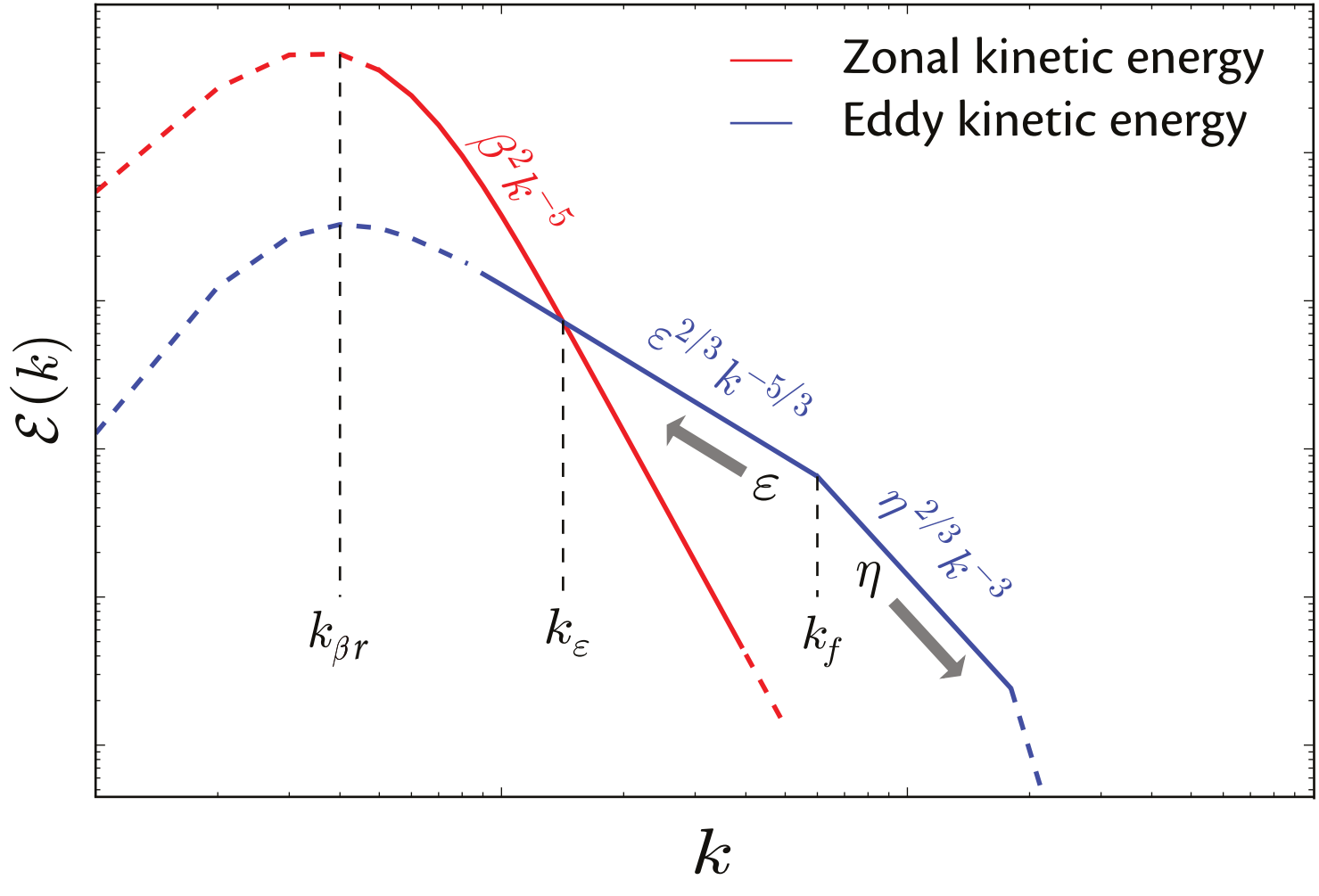

Zonal kinetic energy
Eddy kinetic energy
$\beta^2 k^{-5}$
$\varepsilon^{2/3} k^{-5/3}$
ε
$\eta^{2/3} k^{-3}$
η
$k_{\beta r}$
k_ε
k_f
$\mathcal{E}(k)$
k

Fig. 12.5

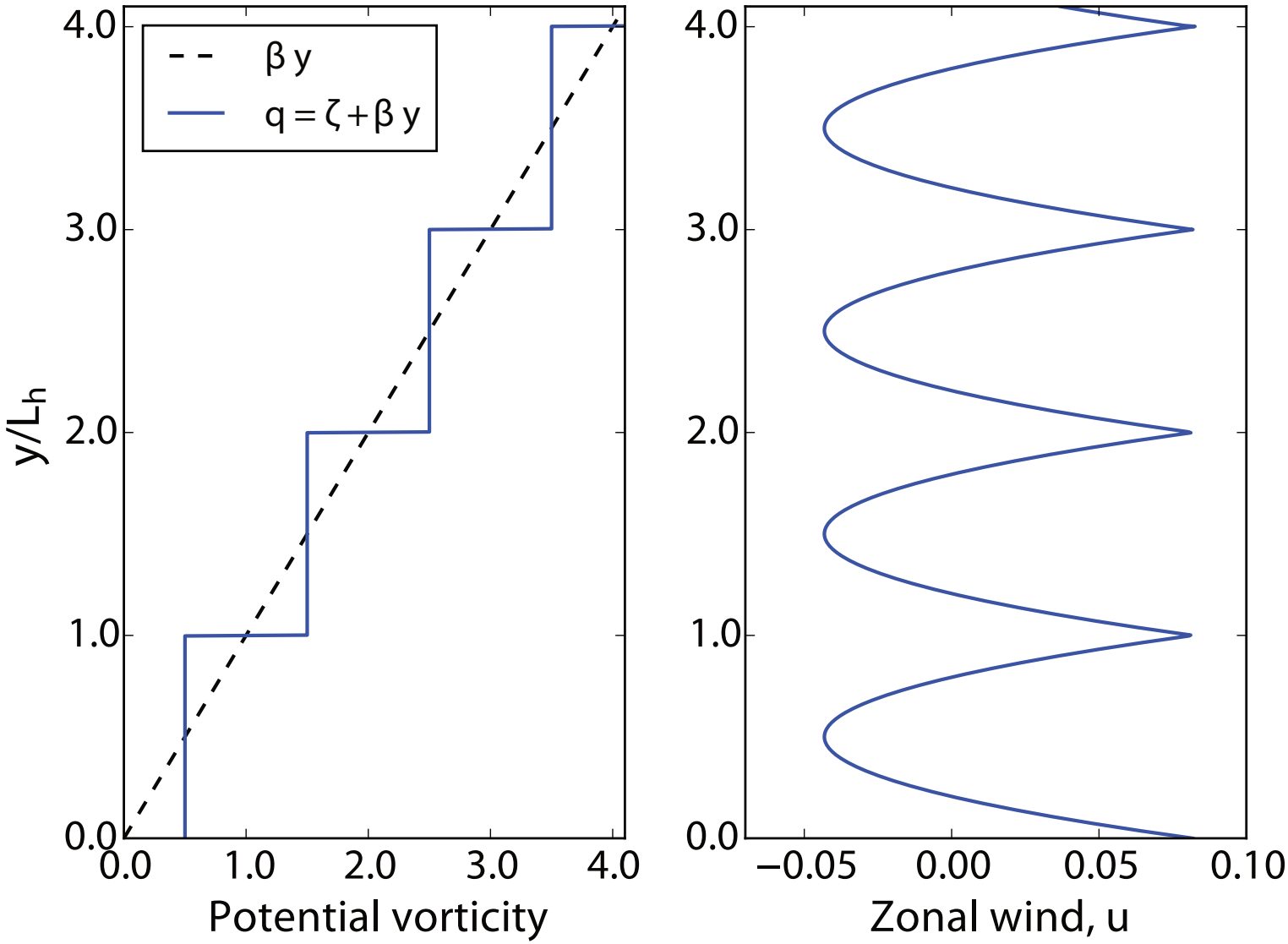

β y
q = ζ + β y
4.0
3.0
2.0
1.0
0.0
y/L_h
0.0
1.0
2.0
3.0
4.0
Potential vorticity
−0.05
0.00
0.05
0.10
Zonal wind, u

Fig. 12.6

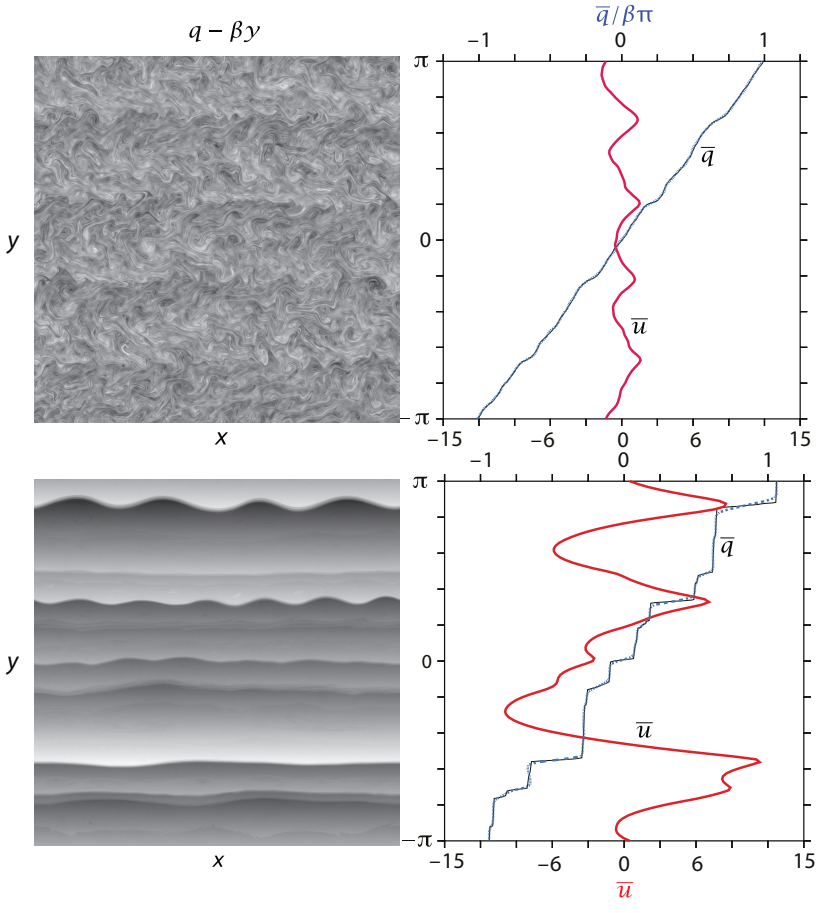

$q - \beta y$
$\overline{q}/\beta\pi$
−1
0
1
π
0
−π
$\overline{q}$
$\overline{u}$
y
x
−15
−6
0
6
15
$\overline{u}$

Fig. 12.7

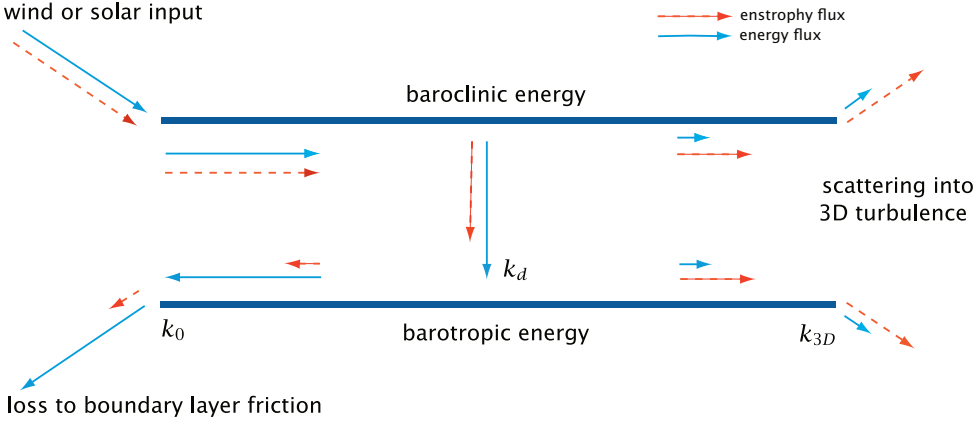

wind or solar input
enstrophy flux
energy flux
baroclinic energy
scattering into
3D turbulence
k_d
k_0
barotropic energy
k_{3D}
loss to boundary layer friction

Fig. 12.8

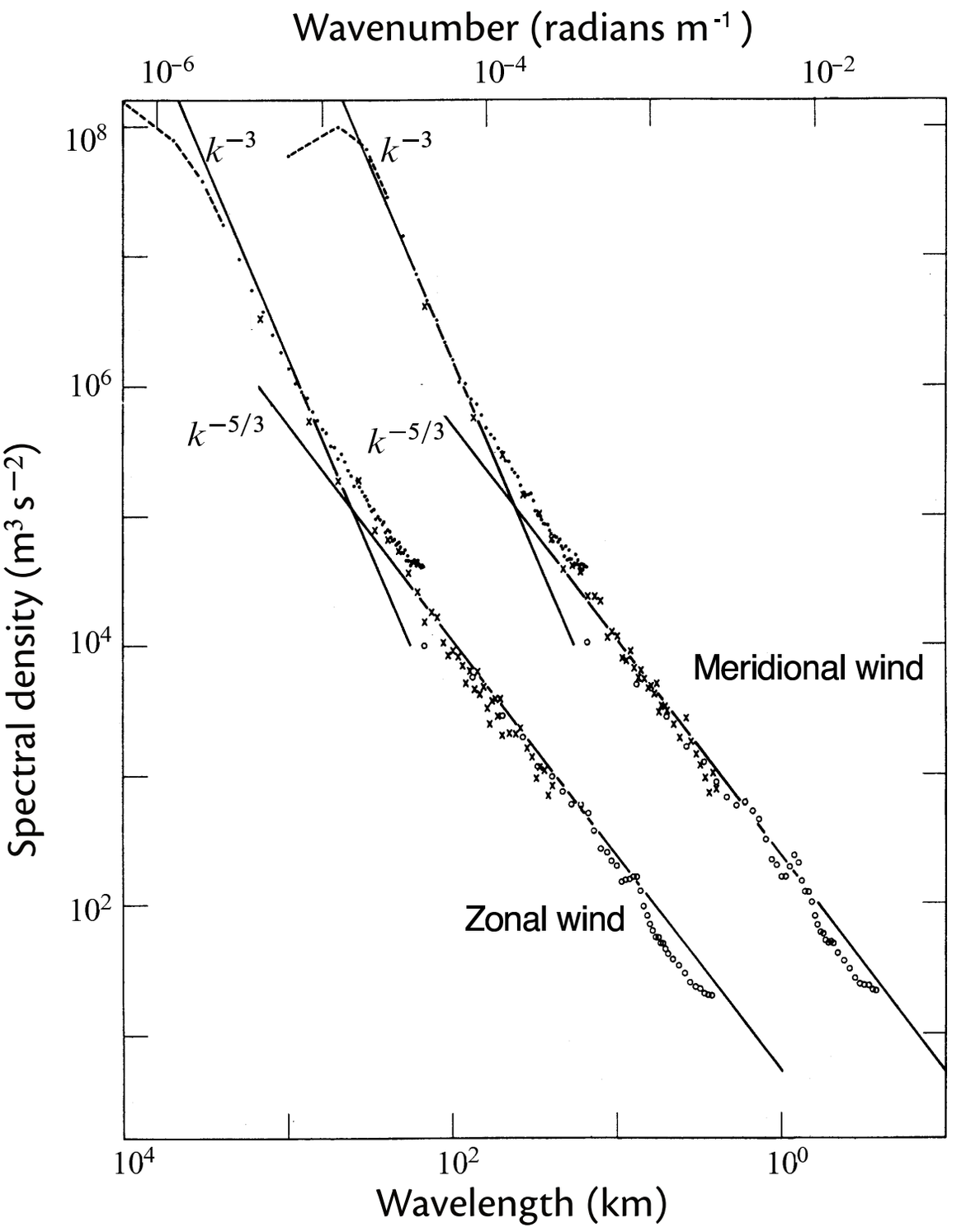

Wavenumber (radians m^{-1})
10^{-6}
10^{-4}
10^{-2}
10^{8}
10^{6}
10^{4}
10^{2}
k^{-3}
k^{-3}
$k^{-5/3}$
$k^{-5/3}$
Meridional wind
Zonal wind
Spectral density (m^3 s^{-2})
10^{4}
10^{2}
10^{0}
Wavelength (km)

Fig. 12.9

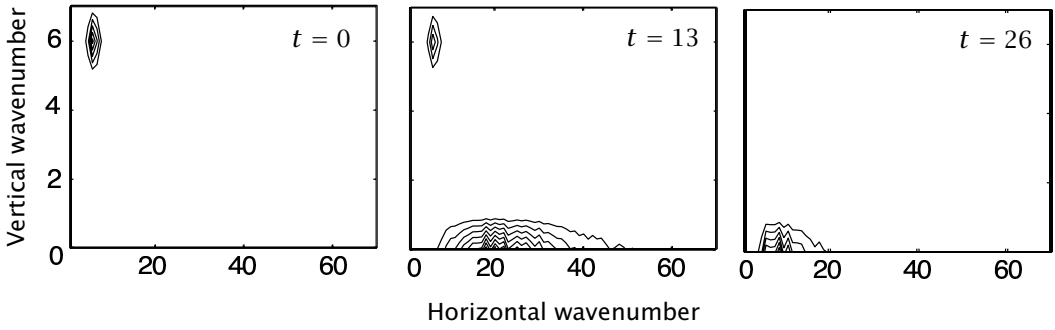

Vertical wavenumber
6
4
2
0
20
40
60
t = 0
t = 13
t = 26
Horizontal wavenumber

Fig. 12.10

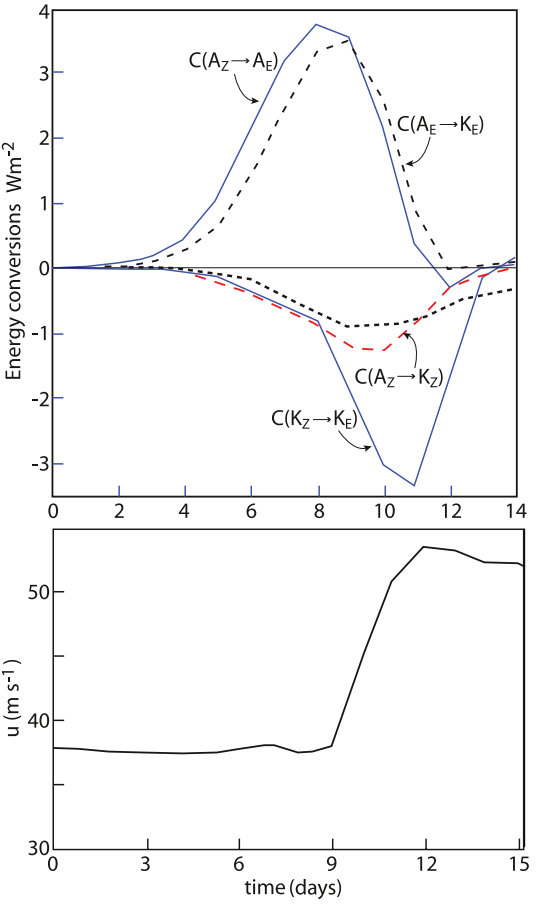

Energy conversions Wm-2
C(AZ→AE)
C(AE→KE)
C(AZ→KZ)
C(KZ→KE)
u (m s-1)
time (days)

Fig. 12.11

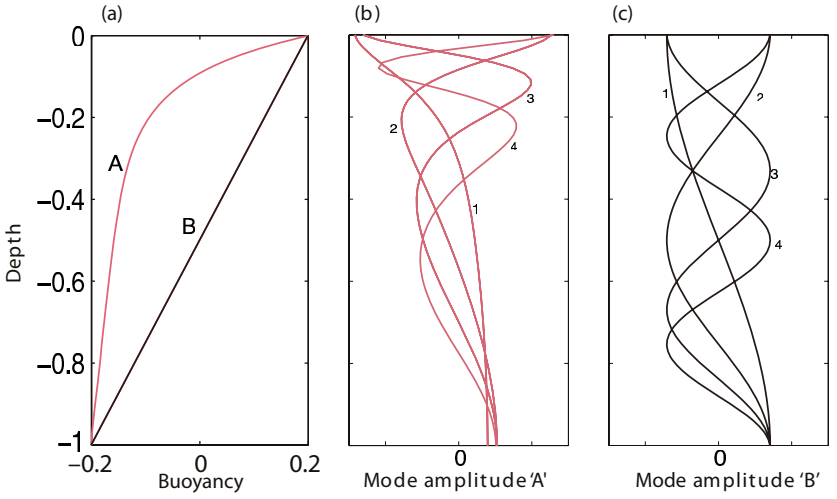

(a)
(b)
(c)
0
−0.2
−0.4
−0.6
−0.8
−1
Depth
A
B
−0.2
0
0.2
Buoyancy
1
2
3
4
0
Mode amplitude 'A'
1
2
3
4
0
Mode amplitude 'B'

Fig. 12.12

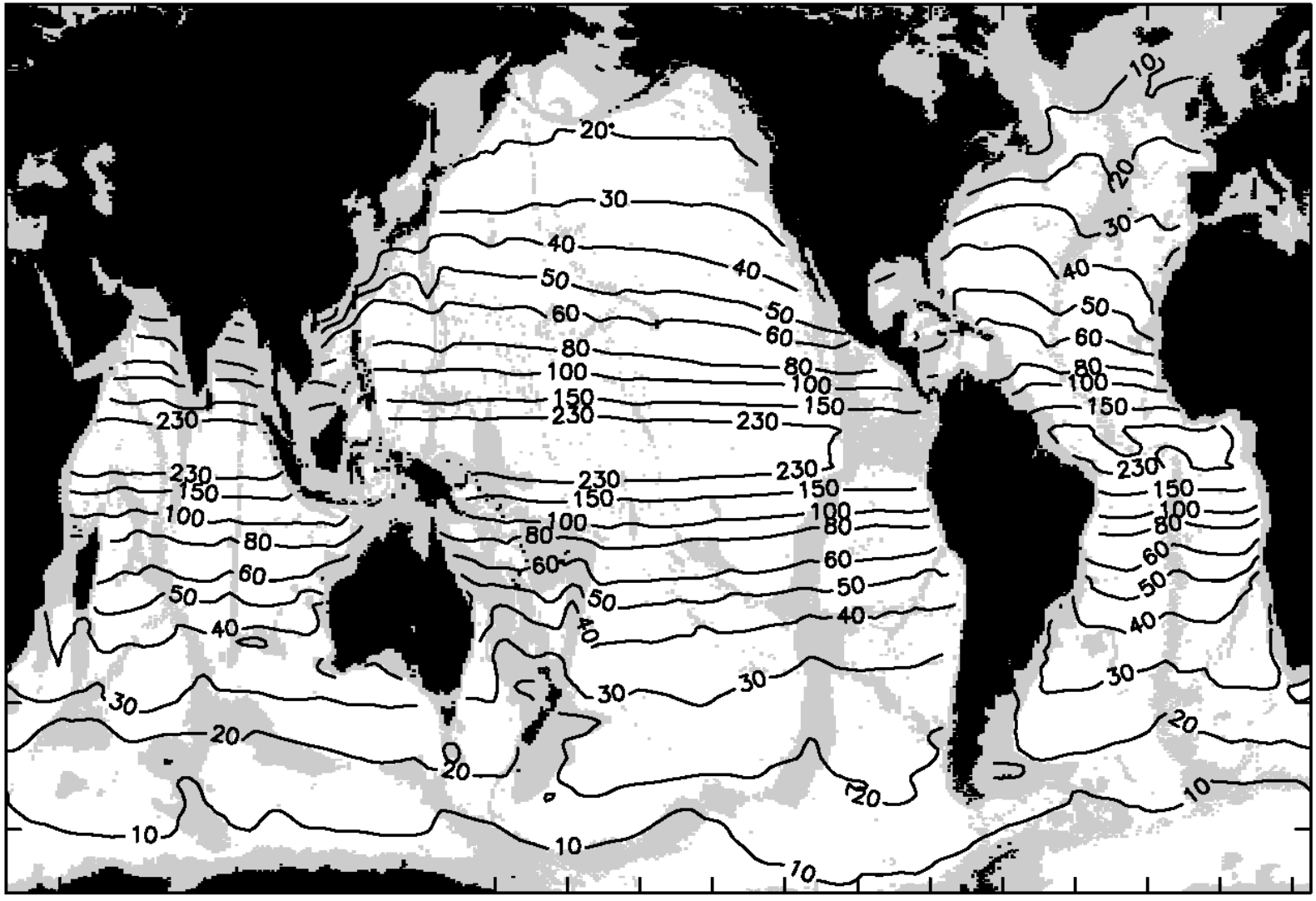


Fig. 12.13

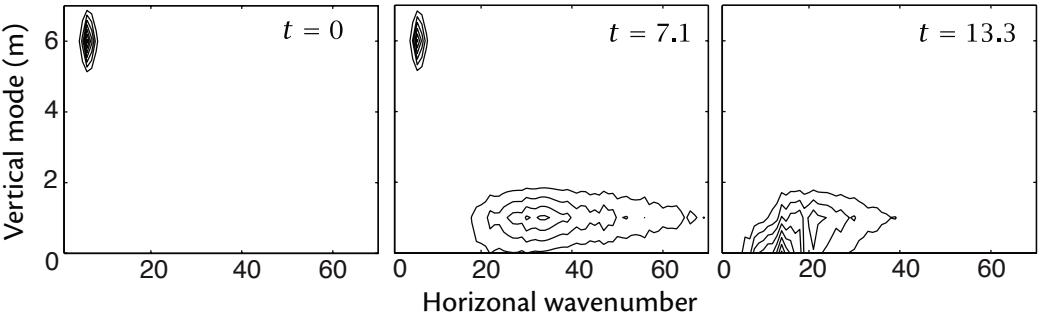

Vertical mode (m)
6
4
2
0
t = 0
t = 7.1
t = 13.3
0
20
40
60
Horizonal wavenumber

Fig. 12.14

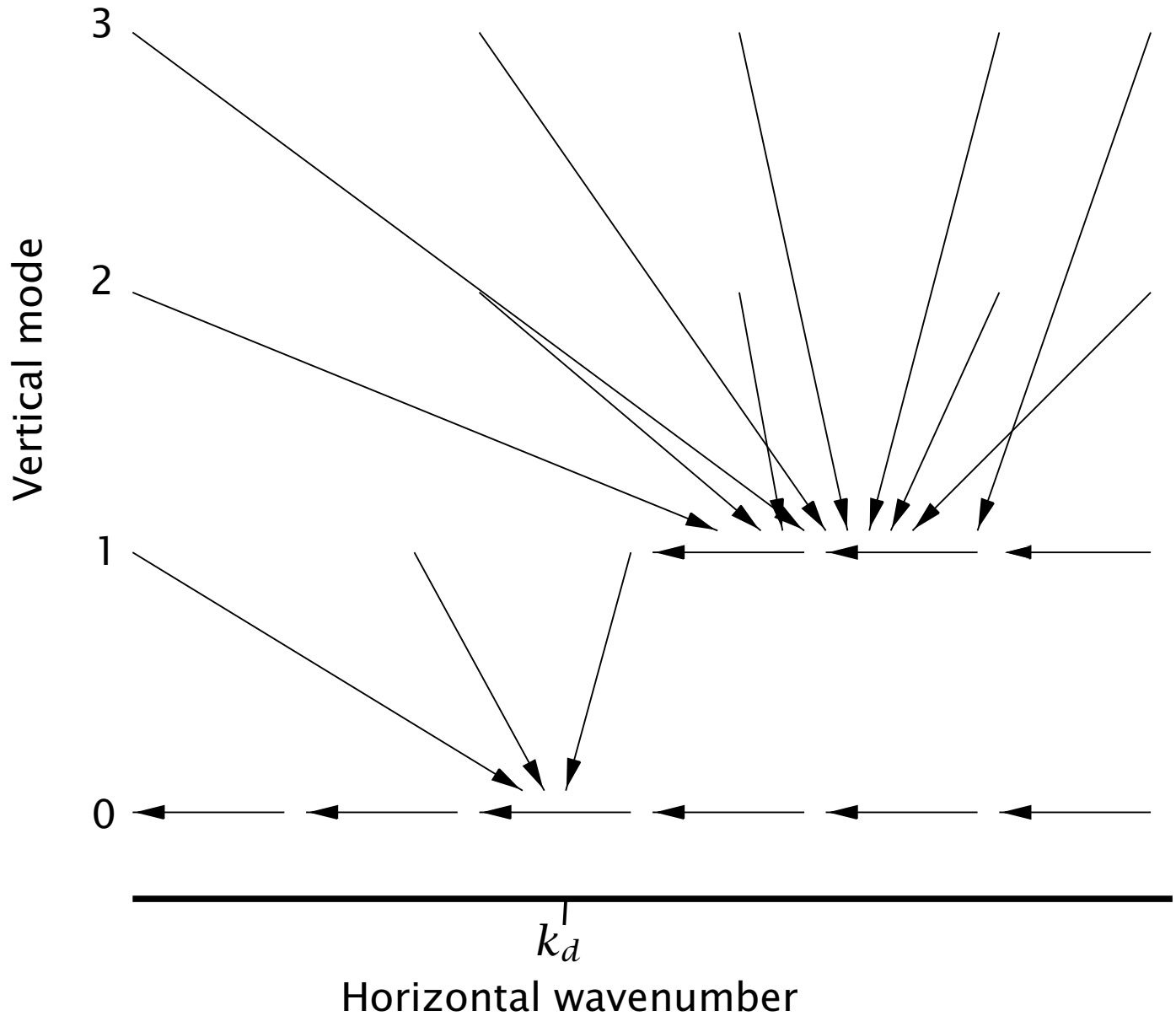


Fig. 12.15

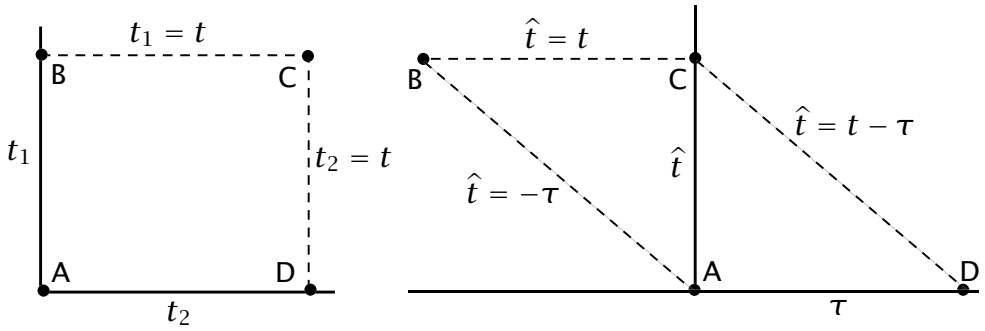


Fig. 13.1

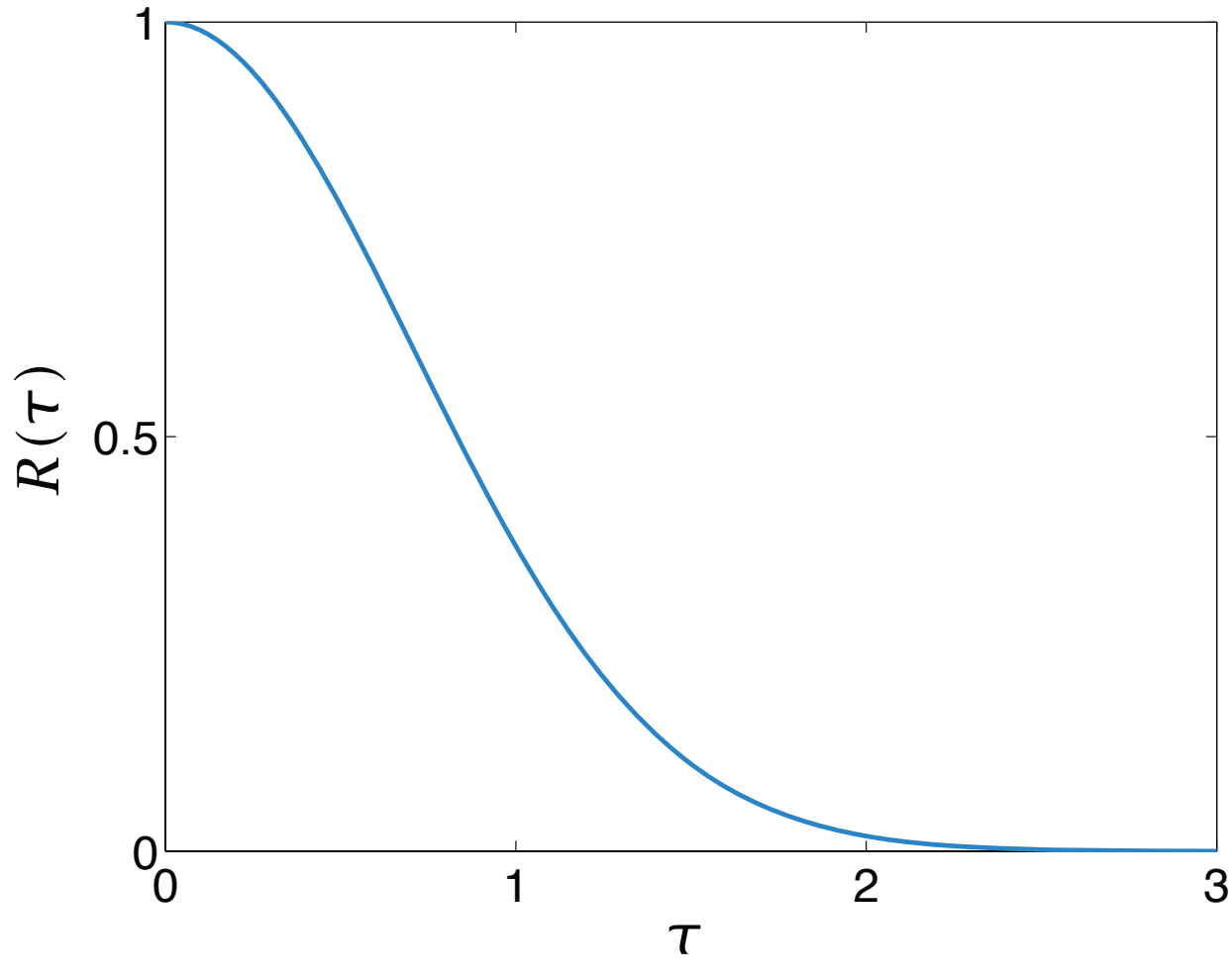


Fig. 13.2

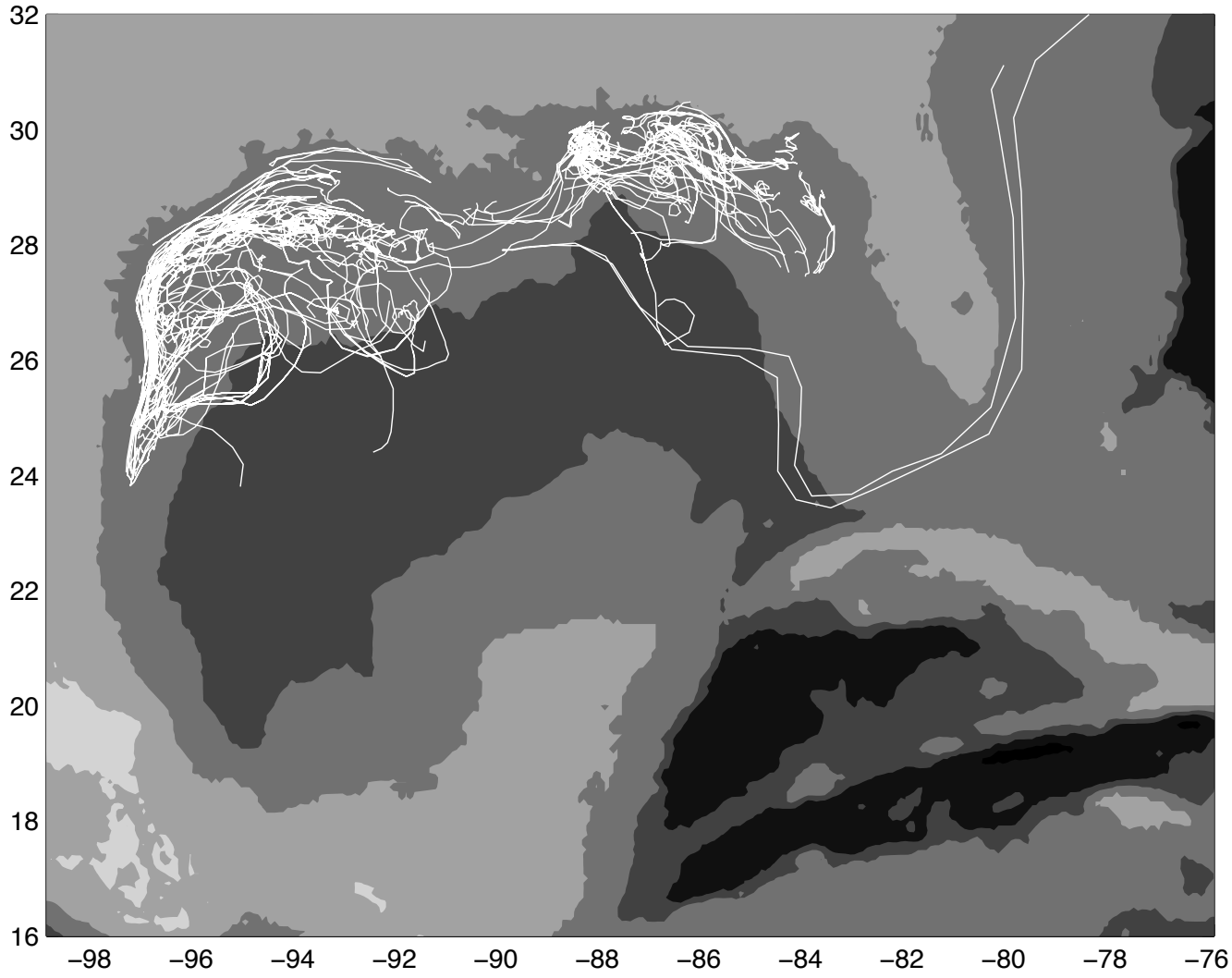


Fig. 13.3

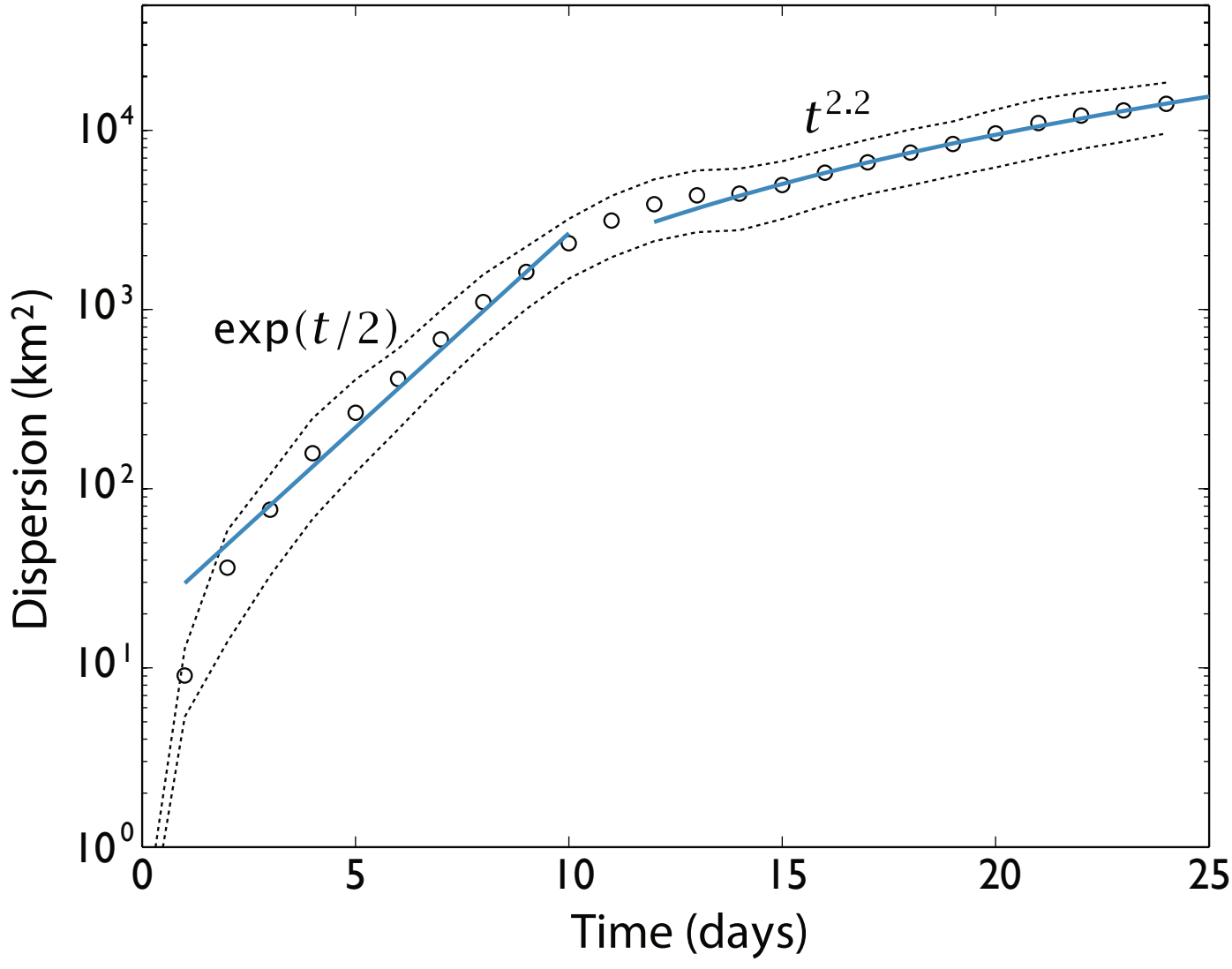

10^4
10^3
10^2
10^1
10^0
Dispersion (km²)
$t^{2.2}$
$\exp(t/2)$
0
5
10
15
20
25
Time (days)

Fig. 13.4

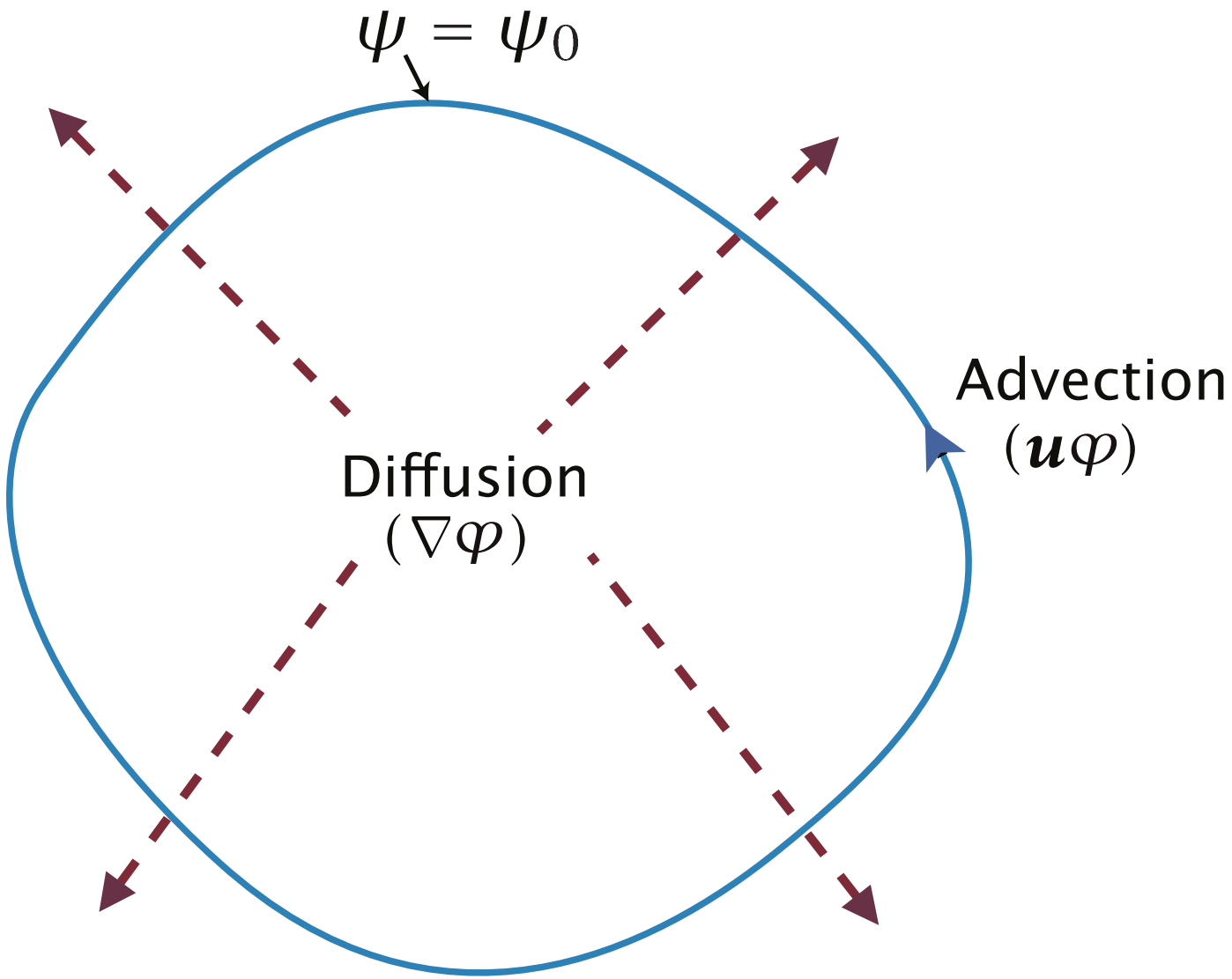

$\psi = \psi_0$
Advection
$(\boldsymbol{u}\varphi)$
Diffusion
$(\nabla\varphi)$

Fig. 13.5

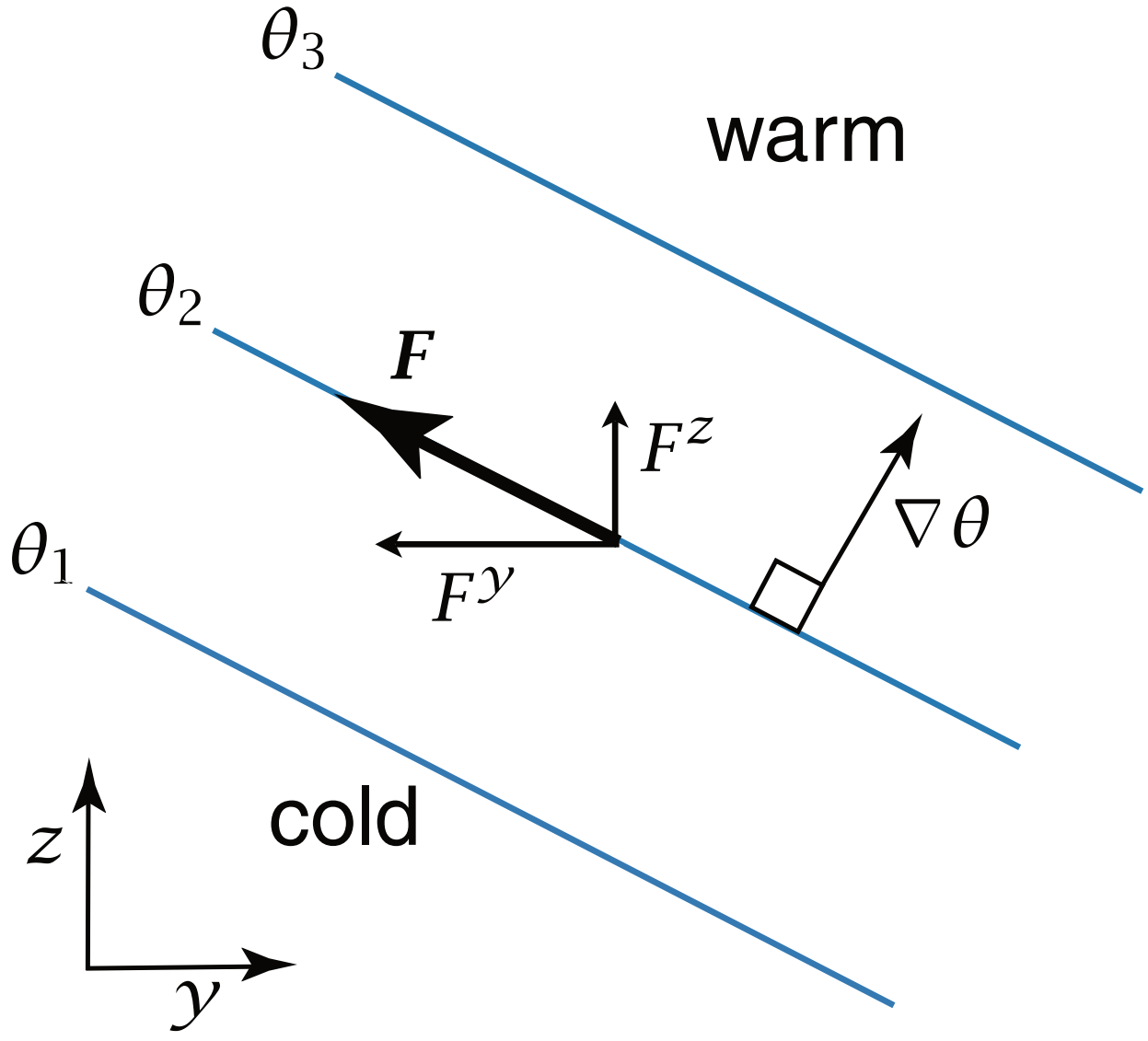

θ_3
warm
θ_2
$\boldsymbol{F}$
F^z
$\nabla\theta$
θ_1
F^y
cold
z
y

Fig. 13.6

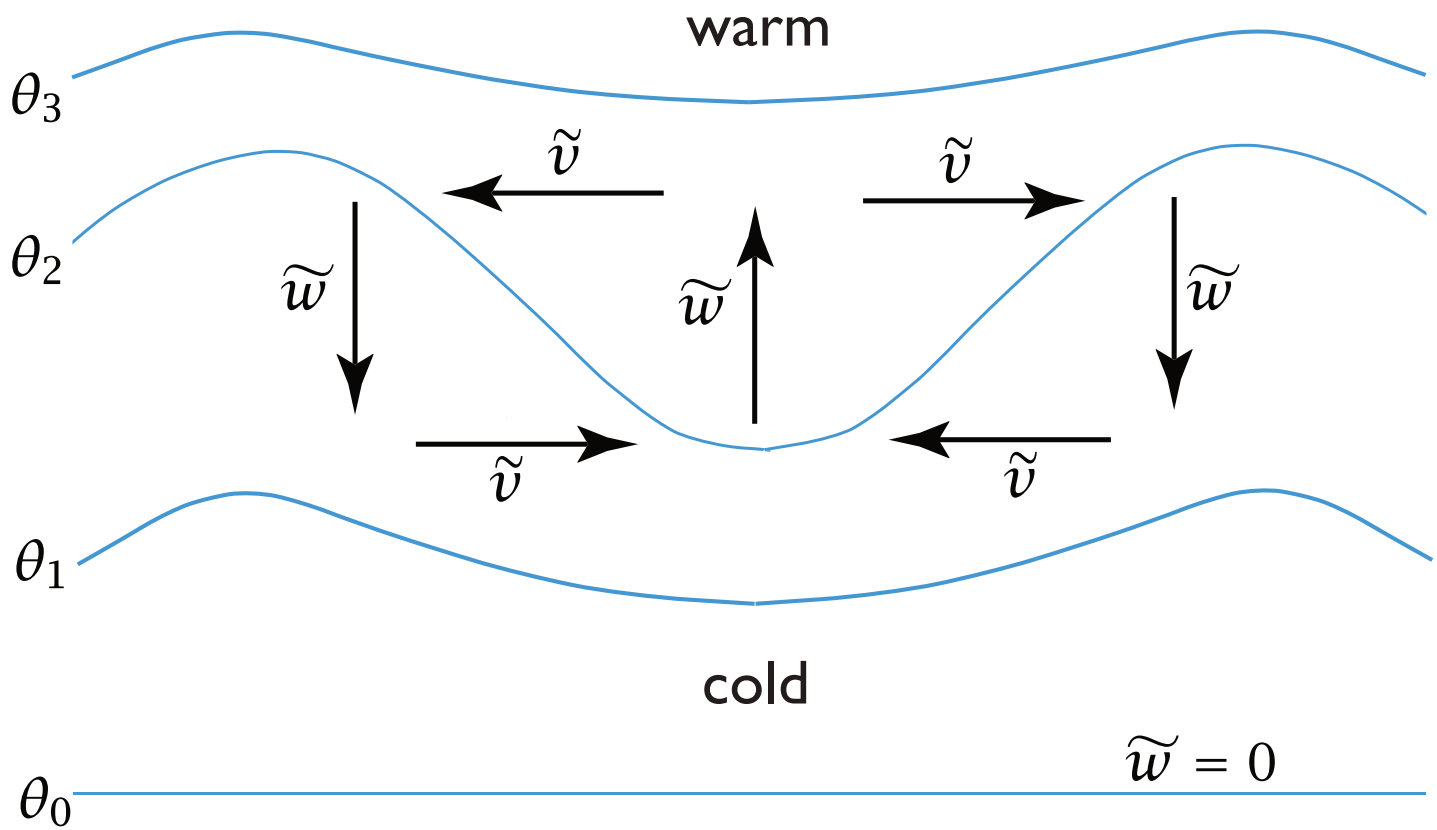

warm
θ_3
θ_2
θ_1
θ_0
$\tilde{v}$
$\tilde{v}$
$\tilde{w}$
$\tilde{w}$
$\tilde{w}$
$\tilde{v}$
$\tilde{v}$
cold
$\tilde{w} = 0$

Fig. 13.7