

MIT OpenCourseWare  
<http://ocw.mit.edu>

12.003 Atmosphere, Ocean and Climate Dynamics  
Fall 2008

For information about citing these materials or our Terms of Use, visit: <http://ocw.mit.edu/terms>.

# Contents

0.1	Preface . . . . .	10
0.1.1	Natural fluid dynamics . . . . .	10
0.1.2	Rotating fluid dynamics . . . . .	13
0.1.3	Holism . . . . .	16
<b>I</b>	<b>The Atmosphere</b>	<b>19</b>
<b>1</b>	<b>Characteristics of the atmosphere</b>	<b>21</b>
1.1	Geometry . . . . .	21
1.2	Chemical composition of the atmosphere . . . . .	22
1.3	Physical properties of air . . . . .	23
1.3.1	Moist air . . . . .	25
<b>2</b>	<b>The global energy balance</b>	<b>29</b>
2.1	Effective planetary temperature (emission temperature) . . . . .	29
2.2	The atmospheric absorption spectrum . . . . .	33
2.3	The greenhouse effect . . . . .	34
2.3.1	A simple greenhouse model . . . . .	36
2.3.2	A leaky greenhouse . . . . .	38
2.3.3	A more opaque greenhouse . . . . .	39
<b>3</b>	<b>The vertical structure of the atmosphere</b>	<b>43</b>
3.1	Vertical distribution of temperature and ‘Greenhouse gases’ . . . . .	43
3.1.1	Typical temperature profile . . . . .	43
3.1.2	Atmospheric layers . . . . .	45
3.2	The relationship between pressure and density: hydrostatic balance . . . . .	48
3.3	Vertical structure of pressure and density . . . . .	50

3.3.1	Isothermal atmosphere . . . . .	50
3.3.2	Non-isothermal atmosphere . . . . .	51
3.3.3	Density . . . . .	52
<b>4</b>	<b>Convection</b>	<b>53</b>
4.1	The nature of convection . . . . .	53
4.1.1	Convection in a shallow fluid . . . . .	53
4.1.2	Instability . . . . .	54
4.2	Convection in water (an almost-incompressible fluid) . . . . .	56
4.2.1	Buoyancy . . . . .	56
4.2.2	Stability . . . . .	57
4.2.3	Energetics . . . . .	58
4.2.4	GFD Lab II: convection . . . . .	59
4.3	Dry convection in a compressible atmosphere . . . . .	63
4.3.1	The adiabatic lapse rate . . . . .	63
4.3.2	Potential temperature . . . . .	65
4.4	The atmosphere under stable conditions . . . . .	68
4.4.1	Gravity waves . . . . .	68
4.4.2	Temperature inversions . . . . .	71
4.5	'Moist' convection . . . . .	72
4.5.1	Humidity . . . . .	73
4.5.2	Saturated adiabatic lapse rate . . . . .	74
4.5.3	Radiative-convective equilibrium . . . . .	75
4.6	Convection in the atmosphere . . . . .	76
4.6.1	Convective clouds . . . . .	76
4.6.2	Occurrence and depth of convection . . . . .	77
4.6.3	Where does convection occur? . . . . .	78
<b>5</b>	<b>The Meridional Structure of the Atmosphere</b>	<b>81</b>
5.1	Temperature . . . . .	81
5.1.1	Latitudinal dependence of incoming radiation . . . . .	81
5.1.2	Latitudinal dependence of outgoing radiation . . . . .	82
5.1.3	Meridional structure of temperature . . . . .	84
5.1.4	The energy balance of the atmosphere . . . . .	87
5.2	Pressure and geopotential height . . . . .	88
5.2.1	The height of pressure surfaces . . . . .	88
5.2.2	Geopotential surfaces . . . . .	89
5.3	Moisture . . . . .	90

<b>CONTENTS</b>	<b>5</b>
-----------------	----------

5.4 Winds . . . . .	95
5.4.1 Distribution of winds . . . . .	95
<b>6 The equations of fluid motion</b>	<b>103</b>
6.1 Differentiation following the motion . . . . .	103
6.2 Equation of motion for a nonrotating fluid . . . . .	106
6.2.1 Forces on a fluid parcel . . . . .	106
6.2.2 The equation of motion . . . . .	110
6.2.3 Hydrostatic balance . . . . .	111
6.3 The continuity equation . . . . .	111
6.3.1 Incompressible flow . . . . .	112
6.3.2 Compressible flow . . . . .	112
6.4 Equation of motion for a rotating fluid . . . . .	114
6.4.1 GFD Lab III: radial inflow . . . . .	114
6.4.2 Transformation into rotating coordinates . . . . .	119
6.4.3 The rotating equation of motion . . . . .	121
6.4.4 Experiments with Coriolis forces on a parabolic rotating table . . . . .	123
6.4.5 Geostrophic motion . . . . .	129
6.4.6 The Taylor-Proudman Theorem . . . . .	132
6.4.7 The thermal wind equation . . . . .	135
6.4.8 Subgeostrophic flow: the Ekman layer . . . . .	143
6.5 Putting things on the sphere . . . . .	148
6.5.1 GFD Lab X: An experiment on the Earth's rotation . .	148
6.5.2 The centrifugal force, modified hydrostatic balance and geopotential surfaces on the sphere . . . . .	150
6.5.3 Components of the Coriolis force on the sphere: the Coriolis parameter . . . . .	152
6.6 Geostrophic balance on the sphere . . . . .	154
6.6.1 Small Rossby number flow . . . . .	154
6.7 Thermal wind in pressure coordinates . . . . .	163
6.7.1 Thermal wind expressed in terms of potential temperature . . . . .	164
<b>7 The general circulation of the atmosphere</b>	<b>169</b>
7.1 The tropical Hadley circulation . . . . .	169
7.2 The midlatitude circulation . . . . .	173
7.2.1 Energy stored in the thermal wind . . . . .	174

7.2.2	Available potential energy . . . . .	175
7.2.3	Baroclinic instability . . . . .	178
7.2.4	GFD Lab XI: baroclinic instability of the thermal wind	180
7.3	The ‘big picture’ of the atmospheric heat (and momentum) budget . . . . .	182
7.3.1	Energy requirements, as deduced from observations . .	182
7.3.2	Incorporating eddy transfer in to our general circulation theory . . . . .	185
<b>II</b>	<b>The Ocean</b>	<b>189</b>
<b>8</b>	<b>The ocean and its circulation</b>	<b>191</b>
8.1	Physical characteristics of the ocean . . . . .	192
8.1.1	Properties of seawater; equation of state . . . . .	193
8.1.2	Temperature and salinity structure . . . . .	196
8.1.3	The mixed layer and thermocline . . . . .	201
8.2	The observed circulation . . . . .	204
8.3	Inferences from geostrophic and hydrostatic balance . . . . .	207
8.3.1	Ocean surface structure and geostrophic flow . . . . .	208
8.3.2	Deep geostrophic flow . . . . .	211
<b>9</b>	<b>The wind-driven circulation</b>	<b>213</b>
9.1	The wind stress and Ekman layers . . . . .	213
9.1.1	Balance of forces in the Ekman layer . . . . .	215
9.1.2	Wind-driven Ekman pumping . . . . .	216
9.2	Response of the interior ocean to Ekman pumping . . . . .	220
9.2.1	Interior balances . . . . .	220
9.2.2	Taylor-Proudman on the sphere . . . . .	221
9.2.3	GFD Lab XIII: Wind-driven ocean gyres . . . . .	225
9.2.4	The wind-driven gyres and western boundary currents	226
9.3	The depth-integrated circulation . . . . .	228
9.3.1	Mass transport of gyres: western boundary current speeds . . . . .	231
9.4	Effects of inhomogeneity . . . . .	231
9.4.1	Taylor-Proudman in a layered ocean . . . . .	233
9.5	Ocean eddies . . . . .	236
9.5.1	Observations of ocean eddies . . . . .	236

9.5.2 Baroclinic instability in the ocean . . . . .	238
<b>10 The thermohaline circulation of the ocean</b>	<b>243</b>
10.1 Sources of deep water . . . . .	243
10.2 Time scales and intensity of thermohaline circulation . . . . .	249
10.3 Abyssal circulation schematic deduced from ‘Taylor-Proudman’	250
10.4 Observations of the abyssal circulation . . . . .	252
10.5 GFD Lab XIV: The thermohaline circulation . . . . .	257
10.6 Why western boundary currents? . . . . .	258
10.6.1 GFD Lab XV: Source sink flow in a rotating basin . . .	260
<b>11 The ocean’s role in climate</b>	<b>263</b>
11.1 Ocean Heat storage . . . . .	263
11.2 Ocean heat transport . . . . .	264
11.2.1 Mechanisms of ocean heat transport . . . . .	266