## **Contents**

1	Introduction				
	1.1	Goals of these Notes			
	1.2	limate System	3		
		1.2.1	Components of the Climate System		
		1.2.2	Global Radiation Balance of the Climate System	5	
	1.3	Purpo	se and Limitations of Climate Modelling	5	
	1.4	•			
	1.5	<del>-</del>			
		1.5.1	Simulation of the Twentieth Century		
			with the Goal to Quantify the Link Between		
			Increases in Atmospheric CO <sub>2</sub> Concentrations		
			and Changes in Temperature	15	
		1.5,2	Decrease in Arctic Sea Ice Cover Since Around 1960	16	
		1.5.3	Summer Temperatures in Europe Towards		
			the End of the Twenty-First Century	17	
		1.5.4	CO <sub>2</sub> Emissions Permitted for Prescribed		
			Atmospheric Concentration Paths	18	
		1.5.5	Prediction of the Weak El Niño of 2002/2003	19	
	1.6	Concl	usions	21	
2	Mod	lel Hier	earchy and Simplified Climate Models	25	
_	2.1		chy of Physical Climate Models		
	2.2	Point Model of the Radiation Balance			
	2.3				
	2.5		ion of First Order	37	
	2.4		te Sensitivity and Feedbacks		
		2.4.1	Ice-Albedo Feedback		
		2.4.2	Water Vapour Feedback		
		2.4.3			
		2.4.4			
		2.4.5	•		

xii Contents

3	Describing Transports of Energy and Matter						
	3.1	Diffusion	53				
	3.2	Advection	55				
	3.3	Advection-Diffusion Equation and Continuity Equation	56				
	3.4	Describing Small- and Large-Scale Motions					
	3.5	Solution of the Advection Equation					
		3.5.1 Analytical Solution	61				
		3.5.2 Numerical Solution					
		3.5.3 Numerical Stability, CFL Criterion					
	3.6	Further Methods for the Solution of the Advection Equation					
		3.6.1 Euler Forward in Time, Centered in Space (FTCS)					
		3.6.2 Euler Forward in Time, Upstream in Space (FTUS)					
		3.6.3 Implicit Scheme					
		3.6.4 Lax Scheme					
		3.6.5 Lax-Wendroff Scheme					
	3.7	Numerical Solution of the Advection-Diffusion Equation					
	3.8	Numerical Diffusion					
	5.0	Traincreal Diffusion	, 0				
4	<b>Energy Transport in the Climate System</b>						
	and Its Parameterisation						
	4.1	Basics	79				
	4.2	Heat Transport in the Atmosphere	79				
	4.3	Meridional Energy Balance Model	83				
	4.4	Heat Transport in the Ocean	85				
_	Tmiti	al Value and Boundary Value Problems	Ω1				
5							
	5.1	Basics  Direct Numerical Solution of Poisson's Equation					
	5.2						
	5.3	Iterative Methods					
		5.3.1 Methods of Relaxation					
		5.3.2 Method of Successive Overrelaxation (SOR)	95				
6	Lar	ge-Scale Circulation in the Ocean	97				
•	6.1	Material Derivative					
	6.2	Equation of Motion					
	6.3	Continuity Equation					
	6.4	Special Case: Shallow Water Equations					
	6.5	Different Types of Grids in Climate Models					
	6.6	Spectral Models					
	6.7	Wind-Driven Flow in the Ocean (Stommel Model)					
	0.7	6.7.1 Determination of the Stream Function					
		6.7.2 Determination of the Stream Function					
	60						
	6.8	Potential Vorticity: An Important Conserved Quantity	11/				

Contents xiii

7	Large-Scale Circulation in the Atmosphere				
	7.1	Zonal and Meridional Circulation	123		
	7.2	The Lorenz–Saltzman Model	128		
8	Atmosphere-Ocean Interactions				
	8.1	Coupling of Physical Model Components			
	8.2	Thermal Boundary Conditions			
	8.3	Hydrological Boundary Conditions	142		
	8.4	Momentum Fluxes			
	8.5	Mixed Boundary Conditions			
	8.6	Coupled Models			
9	Multiple Equilibria in the Climate System				
	9.1	Abrupt Climate Change Recorded in Polar Ice Cores			
	9.2	The Bipolar Seesaw			
	9.3	Multiple Equilibria in a Simple Atmosphere Model			
	9.4	Multiple Equilibria in a Simple Ocean Model			
	9.5	Multiple Equilibria in Coupled Models			
	9.6	Concluding Remarks			
Re	References				
Ind	Index				