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Dynamics of the Tropical Atmosphere and Oceans

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For:

*Benjamin David, Chloe, Caitlyn and Jack Webster and Clara Whelan,
and, especially*

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Preface

My interest in tropical meteorology evolved in a number of ways. After finishing my undergraduate work and completing my meteorologist training with the Bureau of Meteorology in Australia, I was assigned as a very junior forecaster to the Darwin Airport forecast office in the far north of Australia. There appeared to be two seasons in Darwin: the “dry” and the “wet” or, alternatively, the “boring” and the “unknown.” During the dry, except for occasional early morning fog, a day of fine weather and southeasterly trade winds tended to follow a day of fine weather and etc., rather repetitively. The wet was completely different and each day was a challenge. Satellite meteorology was in its infancy. Beyond the very strong diurnal cycle there appeared to be no overriding physical explanation or schema that would help anticipate the development and migration of convective weather events and the occasional tropical cyclone. All forecasts were made using hand drawn synoptic charts and there was little upper air data, especially to the north of Australia. However, I had obtained a copy of Riehl’s (Riehl 1954) and later Riehl 1979 masterpiece on tropical meteorology and it seemed to me that perhaps there might be some order within the seemingly chaotic wet season if one could only find it. Further, Riehl and Malkus (1958) had suggested organization on the grand scale, posing a theory that heat and momentum transports within deep penetrating convection in the equatorial trough were integral parts of the general circulation of the planet. I found both works rather exciting!

So motivated, and armed with a lack of humility, I moved to the United States for graduate work at Florida State University with Professor Michael Garstang who was a fine empiricist. I was lucky enough to be chosen to attend the National Center for Atmospheric Research graduate student summer workshop on thermal convection and where I was intrigued with the developing field of low-latitude dynamics. It was there I met Professors Jule Charney and Norman Phillips, who were to become my advisors at MIT. Charney was attempting to find a balanced dynamic system for the tropics that was equivalent to the quasi-geostrophic system he had formulated for the extratropics. At that

time he was also trying to understand the rapid spin-up of tropical cyclones. Phillips was particularly concerned with modeling the global general circulation, handling the tropics adequately and accounting for convection in a realistic manner. Both were aware of the very recent pioneering work of Professor Taroh Matsuno (1966) on the existence of wave-forms having maximum variance close to the equator. But no one had much idea of how these tropical modes were excited. The development of an adequate in situ instability process proved difficult and the propagation of extratropical waves through the tropical easterlies had its own theoretical problems. To a large degree, the interdependence of the tropics and the tropics was not understood at all. It was within this environment that I commenced my PhD work.

There was an immediacy in the solution of some of these issues. During the early years of numerical weather prediction with its concentration on the extratropics, it was apparent that what occurred in the tropics influenced higher latitudes very rapidly. Hence, a forecast with a time horizon beyond a few days needed to be generated by a global model that was fueled by a global initial data. This meant that predicting mid-latitude weather required understanding tropical processes and the convective elements of which they are comprised. Perhaps because of this immediacy, our knowledge of tropical atmospheric, oceanographic, and land-surface processes would progress substantially during the next few decades. These advances have come from increased observations and a surge of theoretical insights. Much of progress has been built on the results of a large number of dedicated field campaigns specifically designed to increase understanding of components of the tropical system.

Understanding the dynamics of tropical circulations is important, not only for predicting mid-latitude weather, but because weather and climate variations in the tropics impact about half of the global population directly. Within the monsoon regions, for example, vagaries in annual rainfall create periods of either agricultural scarcity or abundance, hardship or plenty. “Active” and “break” periods of the monsoon impart periods of

short-lived drought and flood to the region and they have been notoriously difficult to predict and remain so to a large degree today.

My interest in tropical meteorology and participation in a number of field experiments in tropical regions led me toward applying some of the growing knowledge of tropical dynamics for prediction in monsoon regions. I was fortunate to spend a sabbatical (1991–1992) at the European Centre for Medium Range Weather Forecasts working with Tim Palmer. This was a time when numerical weather prediction was undergoing a major transformation toward ensemble prediction that would enable probabilistic forecasts at longer lead times. Such techniques allowed Tim Palmer, Tom Hopson, Jun Jian and me, among others, to produce probability flood forecasts for the monsoon regions of Bangladesh that gave users the knowledge to make decisions based on the likelihood of an event occurring and the occurrent loss if action were not taken. Rural communities, anticipating the occurrence of a flood based on these forecasts were able to save the equivalent of an annual income by moving livestock to higher ground, early harvesting, and evacuation.

This text rests on both a “reductionist” and “holistic” perspective. The book describes the basic physics of individual elements of the large-scale circulations like equatorially trapped waves, the El Niño, and the monsoon. Such is the “reductionist” perspective. The “holistic” approach acknowledges that new or emergent features of tropical circulation cannot be deduced from the properties of the individual elements alone. Without a knowledge of the basic physics of the components of a complex system, it is difficult to assess whether the results of a complex coupled climate model, for example, are realistic. However, without a complex model that encompasses the individual phenomena as well as the broader context and interactions with the larger-scale environment, it is difficult to determine a range of possible outcomes.

The text is aimed at the advanced undergraduate or an early career graduate student. A basic level of fluid dynamics and thermodynamics would be an advantage, but I have attempted to place complicated concepts in a broader and simpler context. The book is also intended to serve as a general reference book for scientists interested in tropical phenomena and their relationship with the broader climate system. The focus of this text is on the fundamental aspects of the large-scale coupled dynamics of the tropical system. Tropical cyclones are considered principally in terms of genesis processes related to the large-scale environment. There are a number of texts that deal with important details of tropical cyclones. To do this here in an adequate manner would double the size of the text.

I started this project many years ago and it has progressed with many stops and starts. Part of the problem is accounting for changes in a rapidly evolving field. What is recorded in the text has been developed for and presented in many graduate classes. From one class to the next, new knowledge is relatively easy to incorporate by updating and changing class notes. However, in writing a text eventually one needs to draw a line. I think Sir Winston S. Churchill may have said it best:

Writing a book is an adventure. To begin with it is a toy and an amusement. Then it becomes a mistress, then it becomes a master, then it becomes a tyrant. The last phase is that just as you are about to be reconciled to your servitude, you kill the monster and fling him to the public.

So, for better or for worse . . . !

Reno, Nevada, USA
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PJW

Acknowledgments

Throughout my career, I have had the privilege to work with many gifted students and colleagues. In fact, there are 31 young scientists whom I mentored on their way to their doctorates, in addition to many postdoctoral fellows who were part of our research group through the years. They constituted a diverse and international cadre, hailing from Romania, China, Australia, the United Kingdom, Brazil, Colombia, the United States, Japan, Russia, India, Taiwan, and Korea. Many have risen to positions of prominence, making significant contributions in their chosen careers in academia, research laboratories, and the private sector.

Most of all I have to thank my students and post-docs. I think one of the great privileges of being a professor is to be associated with bright young minds, watching them develop through hard work to become shining skeptical scientists. I know that the faculty–student interaction is often thought to be “top-down” but I feel that it is at least an equal interaction or perhaps even weighted “bottom-up.” Over the years, I think all of us have enjoyed the to and fro of what were often exciting group meetings.

I would like to acknowledge two members of my research group in particular, Drs. Hai-Ru Chang and Violeta Toma, both of whom contributed substantially to earlier versions of the manuscript. Hai-Ru has been an integral component of my research group since the mid-1980s. His rigor and theoretical knowledge of fluid dynamics have been a great benefit to our collective efforts. Violeta is a gifted diagnostician and was instrumental in producing analyses of near-equatorial phenomena, designing models and conducting many simulations. She has also made fundamental contributions to the concept of global synchronicity described in Chapter 11. I would also like to thank both Hai-Ru and Violeta for their critical assessment of various parts of the text. Thanks are also due to Dr. Ferdinand Hirata who carefully produced many of the figures.

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Over the years, I have had many colleagues to whom I have moaned and groaned about writing a book. They have remained cheerful, more so than me I must admit, and convinced me that it is a worthwhile endeavor. They have made both substantive and philosophical contributions that I have welcomed very much. George Kiladis and Matt Wheeler persisted (patiently) in convincing me in how convection and equatorial modes interact. George has been very generous with his time in discussing large sections of pertinent text. Robert Houze of the University of Washington has reminded me on many occasions how convective elements comprise an integral part of the dynamics of the tropics. Thanks are due to my Australian colleagues, Greg Holland, John McBride, and also “fellow (field expedition) traveller” Bob Grossman, who all nudged me on many occasions towards the realization that there is reality beyond theory or model results. I have come to realize that the empiricism embodied in their work and that offered by scientists such as Richard Johnson and Bob Houze is a vital component of the tropical puzzle. With respect to empiricism, I appreciate the inspiration of Prof. Michael Garstang, with whose research group I was briefly associated when I first arrived in the US. He was rather forceful in reminding many of us that the tropics was a complicated system and that not everything can be encapsulated in a neat set of equations. I also appreciate my colleague Professor Tim Palmer at Oxford for introducing me to the wonderful concept of uncertainty, chaos, and probabilistic forecasting during a sabbatical at ECMWF that has had a profound influence on subsequent work. Professor Sharon Nicholson of Florida State University provided data and ideas about the meteorology of near-equatorial Africa and how meteorology and climate differs markedly from one tropical region to another. I appreciate Graeme Stephens of NASA, who at an early stage of my career explained painstakingly the role of clouds in radiative forcing of the tropical atmosphere. We started our discussions in

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A large part of my career has been involved in field expeditions. I have come to believe that these times in the field account for much of the progress we have made in tropical meteorology. The data collected is invaluable but they are catalysts for thought. Although expeditions arise from curiosity, implementation is often beyond the capabilities of just the curious. The transformation of ideas to results requires expert logistical support. Such support has come from the University Corporation of Atmospheric Research’s (UCAR) Joint Office for Science Support led for many years by Karyn Sawyer. I first met Karyn in 1978 in Kolkata, India, during the Summer Monsoon Experiment and in the many subsequent field adventures that have followed. On numerous occasions her office has made it possible to transform a myriad of ideas to an organized reality, with the result of providing essential data to the larger scientific community.

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Peter J. Webster

Abbreviations

AIRI	All-India Rainfall Index	ENSO	El Niño-Southern Oscillation
AMEX	The Australian Meteorological Experiment	EOF	Empirical Orthogonal Function
AMG	Asian Monsoon Gyre	EPIC	East Pacific Investigation of Climate Processes in the Coupled Ocean-Atmosphere System
AMO	Atlantic Multidecadal Oscillation	ER	Equatorial Rossby wave
ANN	annual	EW	Westward equatorial basis state
APE	Available potential energy	FFT	Fast Fourier Transform
AV	Absolute Vorticity	GARP	Global Atmospheric Research Programme
BP	Before present	GATE	The GARP Atlantic Tropical Experiment
C-C	Clausius-Clapeyron	GCB	Great Cloud Bands
CAPE	Convective Available Potential Energy	GPCP	Global Precipitation Climatology Project (GPCP)
CEPG	Cross-Equatorial Pressure Gradient	HTP	Himalayan-Tibetan Plateau
CIH	column integrated heating	IBTrACS	International Best Track Archive for Climate Stewardship
CIH	Atmospheric Column Integrated Heat	ICSU	International Council of Scientific Unions
CISK	Convective Instability of the Second Kind	IFA	Intensive Flux Array of TOGA COARE
CMIPi	Version “i” of the IPCC Coupled Climate Model Simulations	IGY	International Geophysical Year
CMORPH	NOAA Climate Prediction Center Morphing Technique	IIOE	International Indian Ocean Expedition
dalr	Dry adiabatic lapse rate	IMD	Indian Meteorological Department
DJF	December, January, February	IMET	Improved METeorological buoy
DOF	degrees of freedom	IOD	Indian Ocean Dipole
DWP	Dynamic Warm Pool	IOZM	Indian Ocean Zonal Mode
DYNAMO	Dynamics of the Madden-Julian Oscillation field experiment	IPCC	International Programme on Climate Change
ECC	Equatorial counter current	ISV	Intraseasonal variability
ECMWF	European Centre for Medium Range Weather Forecasts	ITCZ	Intertropical Convergence Zone
ED	Eastward Decaying intraseasonal event	JAA	Japanese Aerospace Agency
EE	Eastward equatorial basis state	JASMINE	Joint Air-Sea Monsoon Interaction Experiment
EI	Eastward Intensifying intraseasonal event	JJA	June, July, August
EIG	Eastward propagating Inertial gravity wave	JJAS	June, July, August, September
EMEX	The Equatorial Mesoscale Experiment	K	Equatorial Kelvin wave
		LGM	Last Glacial Maximum
		LGM	Last Glacial Maximum

MALR	moist adiabatic lapse rate	SICZ	South Indian Convergence Zone
MAM	March, April, May season	SMONEX	Summer component of GARP MONEX
MCZ	maximum cloudiness zone	SO	Southern Oscillation
MCS	mesoscale convective system	SOI	Southern Oscillation Index
MISO	Monsoon Intraseasonal Oscillation	SON	September, October, November season
MJO	The Madden-Julian Oscillation	SPCZ	South Pacific Convergence Zone
MONEX	The GARP Monsoon Experiment	SRES	Special Report on Emission Scenarios
MRG	Mixed Rossby-gravity wave	SSM/I	Special Sensor microwave imager
MSLP	Mean sea level pressure	SST	sea-surface temperature
MYFZ	Mei-Yu-Baiu Frontal zone	TAO	Tropical Atmosphere Ocean Array
NAO	North Atlantic Oscillation	TOA	Top of atmosphere
NASA	National Aeronautic and Space Administration	TOGA	The Tropical Ocean Global Atmosphere Experiment
NCAR	National Center for Atmospheric Research	TOGA COARE	The TOGA Coupled Ocean-Atmosphere Response Experiment
NCEP	National Center for Environmental Prediction	TP	Triple point of water
NEC	North Equatorial current	TRMM	Tropical Rainfall Measurement Mission
NH	Northern Hemisphere	TUTT	Tropical upper-tropospheric trough
NIMBUS III	NASA satellite launched 1969	UARS	Upper-air Research Satellite
Niño-1+2	East Pacific region (5°N-5°S, 90°W-80°W)	UCAR	University Corporation for Atmospheric Research
Niño-3	Central-East Pacific region (5°N-5°S, 150°W-80°W)	WEPOCS	West Pacific Ocean Climate Study
Niño-3.4	Central Pacific region (5°N-5°S, 170°W-120°W)	WIG	Westward propagating Inertial gravity wave
Niño-4	West-Central Pacific region (5°N-5°S, 90°-80°W)	WISHE	The Wind-Induced Surface Heat Exchange mechanism
OLR	Outgoing Longwave radiation at top of atmosphere (TOA)	WMO	World Meteorological Organization
OWP	Ocean Warm Pool (SST > 28°C)	WMONEX	Winter component of GARP MONEX
PE	Potential energy	yr	Year
PIRATA	Prediction and Research Array in the Atlantic		
<i>PKE</i>	perturbation or eddy potential energy		
PMIP	Paleoclimate Model Intercomparison Study		
<i>PV</i>	potential vorticity		
<i>PVS</i>	potential vorticity substance: $PVS = q_s = \sigma q$		
PVU	potential vorticity units (10^{-6} m^2 $\text{s}^{-1} \text{ K kg}^{-1}$)		
QBO	Quasi-Biennial Oscillation		
QBW	Quasi-Biweekly Wave		
RAMA	Research Moored Array for African-Asian-Australia monsoon Analysis and Prediction		
SACZ	South Atlantic Convergence Zone		
SAM	South Asian Monsoon		
SD	standard deviation		
SEC	South Equatorial Current		
SH	Southern Hemisphere		

Symbols

a	Earth planetary radius
\mathbb{A}	first Airy function
\mathbb{B}	second Airy function
α_p	planetary albedo
α_c	cloud albedo
α_{th}	thermal expansion coefficient for sea water
$\frac{\alpha_v}{\rho}$	specific volume ($1/\rho$)
\overline{B}_E	vertically averaged atmospheric moisture transport
B	buoyancy force per unit mass
B_O	Ocean buoyancy force per unit mass
B_F	buoyancy flux

β	latitudinal gradient of Coriolis parameter $d f / d y$	G	scale height (RT/g)
β_S	salinity contraction coefficient of sea water	γ_s	dissipation rate
C	Symbolic Coriolis force	Γ_d	dry adiabatic lapse rate
\bar{C}	integrated circulation	Γ_s	dry adiabatic lapse rate
C'	vortex tube circulation	Γ^2	wave refractive index
C_D	drag coefficient	\bar{H}	mean depth of a shallow fluid
\tilde{c}_g	wave group speed	$H_S(y)$	slope of the shallow fluid needed to maintain a geostrophic background flow
\tilde{c}_g	group velocity vector	$h_B(x, y)$	topography of the lower boundary in a shallow fluid
	$(c_{gx}\tilde{i} + c_{gy}\tilde{j} + c_{gz}\tilde{k})$	$h(x, y)$	perturbation surface displacement in a shallow fluid: equivalent depth
c_{gx}	zonal wave group speed	h_s	ocean steric height
c_{gy}	meridional wave group speed	\mathbb{H}_n	n^{th} order Hermite polynomial
C_p	specific heat of air at constant pressure	$\underline{i}, \underline{j}$ and \underline{k}	Cartesian unit vectors in the x , y and z directions
c_p	wave phase speed $(gH)^{1/2}$	I_E	emitted terrestrial radiation to space at top of atmosphere
c_{px}	zonal wave phase speed	I_S	net surface longwave radiation
c_{py}	meridional wave phase speed	$I_{S\downarrow}$	downward longwave radiation at surface
c_{gz}	vertical wave group speed	$I_{S\uparrow}$	upward longwave radiation at surface
c_{pz}	vertical wave phase speed	J_A	advective flux of potential vorticity substance on an isentropic surface
\tilde{c}	reduced gravity phase speed $(\tilde{g}H)^{1/2}$	J_θ	potential vorticity substance flux on an isentropic surface due to non-adiabatic heating
D	dissipation of kinetic energy	J_F	potential vorticity substance flux on an isentropic surface due to dissipative processes
D_e	depth of the ocean Ekman layer	J_T	total potential vorticity substance flux on an isentropic surface ($=J_A + J_\theta + J_f$)
D_o	depth of no ocean motion	$J_0(z)$	vertical heating function
D_v	Divergence $(\partial u / \partial x + \partial v / \partial y)$	k	longitudinal or zonal wave number
δ -function	Dirac delta function	K_E	kinetic energy
δ	increment	k_i	general wavenumber in direction “ i ”
E	evaporation rate	ξ	wave action density
E_K	Ekman number	κ	ratio of gas constant and specific heat at constant pressure R/C_p
e_v	water vapor partial pressure	$\ln(p)$	log pressure
e_{sv}	saturated vapor pressure	L	lateral scale of a gravity wave
ε_m	long-wave radiation emissivity	l	latitudinal or meridional wave number
ε	energy density of a wave	L, D	representative length and height scales used in scaling
η	absolute vorticity $(\zeta + f)$	L_0	diameter of pond
η_θ	absolute vorticity on an isentropic surface $(\zeta_\theta + f)$	L_H	surface latent heat flux into the atmosphere
θ	potential temperature	L_P	latent heat release due to precipitation
θ_e	equivalent potential temperature		
f	vertical component of Coriolis parameter $(2\Omega \sin \varphi)$		
f_r	representative frequency used in scaling		
F	radiative flux		
\tilde{F}	dissipation or frictional force vector		
F_B	buoyancy flux		
F_O	ocean buoyancy		
F_R	Froude number		
F_W	surface fresh water flux into the ocean ($E-P$)		
g	gravitational acceleration		
\tilde{g}	reduced gravitational acceleration		
G	atmospheric scale height (RT/g)		

L_z	vertical scale	q	potential vorticity on an isentropic surface or Ertel's potential vorticity
L_E	latent heat of evaporation-condensation		
L_F	latent heat of fusion	q_h	potential vorticity in a shallow fluid
L_S	latent heat of sublimation-deposition	q_p	potential vorticity on an isobaric surface
λ	longitude	q_s	potential vorticity substance
\overline{M}_{ic}	vertically integrated Ekman ocean mass flux in direction i .	\mathbb{R}	real part of an expansion
M_g	geostrophic mass transport in the ocean	r	correlation coefficient
δM_g	incremental geostrophic mass transport in the ocean	R	specific gas constant
\overline{M}_i	total vertically integrated ocean mass flux in direction i .	R	Rossby Radius of Deformation
M	mass of a reservoir of a water substance	R_C	Radius of curvature
M_A	angular momentum	R_E	equatorial Rossby Radius of Deformation
m	vertical wave number	R_d	specific gas constant for dry air
m_o	map scaling factor	R_s	specific gas constant for moist air
m	magnitude of mass source/sink	R_E	net radiation at top of atmosphere
μ	latitudinal structure function of mass source/sink μ	R_E	Reynold's Number
\tilde{n}	normal unit vector	R_i	Richardson number
N^2	Brunt-Väisälä frequency	R_{NET}	net radiative flux into an atmospheric or ocean column
v	specific volume anomaly	R_o	Rossby number
Φ	potential	R_S	net surface radiation
φ	latitude	R_v	gas constant for water vapor
ϕ	geopotential	ρ	density
P	Precipitation rate (e.g., mm/ay)	ρ_0	standard density
p	pressure	ρ_w	density liquid water
P_m	measure of the persistence of SST	ρ_a	air density at ocean surface
$p(y), \varrho(y)$	functions defined in equ. (5.11)	S_R	flux of water substance into a reservoir
p_s or p_0	reference or standard pressure often 1000 hPa	S_0	solar radiation arriving at Earth: Solar Constant
$(P-E)$	Precipitation rate minus evaporation rate or net fresh water flux at ocean or land surface	S	net incoming solar radiation top of atmosphere
ψ_i	radiation penetration depth in ocean	S_m	mass source/sink in shallow fluid or time rate of change of mass between isentropes
ψ	Stokes streamfunction	S_H	surface sensible turbulent heat flux
\dot{Q}	total diabatic heating	S_P	sensible heat flux from precipitation
Q_S	total heat flux at the surface	S_S	net surface shortwave radiation
Q_T	total columnar heating of an atmospheric or ocean column	S	static stability
Q_{SP}	sensible heat surface cooling of precipitation	s	salinity
q_v	specific humidity	s_0	standard value of salinity
q_{vs}	saturation specific humidity	σ_{SB}	Stefan-Boltzman constant
q_s	potential vorticity substance of an isentropic surface; $q_S = \sigma q$	σ	isentropic mass density
q_g	geostrophic potential vorticity	T	temperature
		T_A	mean temperature of an atmospheric column
		T_R	residence time of a water substance in a reservoir
		T_S	standard temperature

T_0	primitive, equivalent or radiating planetary temperature	v_g	geostrophic meridional wind component
T_A	average temperature of planetary atmosphere	v_T	measure of the convergence of the trade winds in Pacific Ocean
T_B	infrared cloud brightness temperature	v^*	deviation of the meridional velocity component from zonal average
T_o	surface temperature of a planet		
T_S	surface temperature	W_p	precipitable water in an atmospheric column
T_{SST}	surface temperature of ocean surface	w	vertical wind component (dz/dt)
t	time	w_Z	dZ/dt : vertical velocity in Z
τ_i	wind stress component in direction i	w_p	($= -\bar{G} \ln(p/p_s)$) coordinates. vertical wind component in pressure coordinates (dp/dt)
\bar{U}	background zonal wind	w_e	Ekman vertical velocity component
\bar{U}_{WD}	magnitude of mean zonal wind in westerly duct	Ω	rotation rate of the planet
\bar{U}_{WS}	basic wind shear between 850 hPa and 250 hPa	ϖ	angular velocity
U, V, W	representative scales of the zonal, meridional and vertical velocity components used in scaling	ω	modal frequency
u	zonal wind component	ω_d	Doppler-shifted modal frequency
u^*	deviation of the zonal velocity component from zonal average	\tilde{V}	Vector velocity with components $u\hat{i}$, $v\hat{j}$ and $w\hat{k}$
u_e	zonal Ekman current component	χ	Velocity potential
u_g	geostrophic zonal wind component	ζ	horizontal component of relative vorticity ($\partial v/\partial x - \partial u/\partial y$)
v	solar radiation absorption coefficient	ζ_T	total horizontal component of relative vorticity (mean plus perturbation)
\bar{V}	background meridional wind		turning latitude
\tilde{V}	velocity vector	y_T	height
V_ψ	rotational component of velocity	z	reference height in the atmosphere
V_χ	divergent component of velocity	z_0	height of the Himalayan-Tibetan Plateau
\tilde{V}_g	vector geostrophic velocity	z_m	height of the Himalayan-Tibetan Plateau
v	meridional wind component	Z	vertical coordinate = $-\bar{G} \ln(p/p_s)$
v_e	meridional Ekman current component		