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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
Judith Curry,
and my students, postdoctoral fellows, colleagues and members of my research group through the years.

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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 PJW
September, 2019

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.

The work of our research group is embodied in much of the text. I would like to mention some contributions that are particularly relevant to its major themes: Hye-Mi Kim for her diagnostics of intraseasonal variability and its relationship to tropical cyclone development; Song Yang who pointed out the non-stationarity of the interaction of the El Niño–Southern Oscillation (ENSO) and the Asian monsoon; Chidong Zhang who did initial work on the interaction of equatorially trapped modes and complex basic states and his more recent work on intraseasonal variability; Bill Lau for his insightful coupled ocean–atmosphere modeling over 40 years ago; Hai-Ru Chang who developed the concept of "wave energy" accumulation and emanation; Robert Tomas for determining the role that ocean heat transport played in the evolution and stability of the Asian monsoon and also, with Violeta Toma, on deciphering structure of near-equatorial convection; Carolyn Reynolds who introduced the group into uncertainties brought into forecasts and the regional growth of errors; Johannes Loschnigg and Chris Torrence who have made great strides towards understanding linkages between ENSO and monsoon variability, adding clarity to Normand's (1951) surmise regarding the lag and or lead of variability between ENSO and the Asian monsoon; Victor Magana and Sanjay Dixit who contributed to our understanding of monsoon and ENSO prediction; John Fasullo for perceptions relating westerly wind bursts and the heat balance of the tropical warm pool; Gill Compo for determining the fundamental structures of Asian cold surges and, with John Fasullo, how they alter the meteorology of the equatorial Pacific; Initial work on the Indian Ocean Zonal mode and its utility in prediction was undertaken by Christie Oefke Clarke and Daria Halkidies; Carlos Hoyos for his work on the evolution of the tropical warm pool and the development of a Bayesian prediction scheme for monsoon rainfall; Paula Agudelo for deciphering the physics of the transition of the suppressed phase of intraseasonal variability to its convective phase; Kam Sahami and Galina Chirokova for insightful modeling of Indian Ocean variability; Fernando Hirata and Dave Lawrence for deducing the intricacies of intraseasonal behavior in both the summer and winter monsoon; Matt Widlansky and Fernando Hirata for making great strides towards solving the mystery of the Great Cloud Bands; Manuel Zuluaga who advanced understanding of the role of aerosols in tropical climates; and Sebastian Ortega for developing fundamental insights into how the tropics and the extratropics interact. Matt Wheeler, of course, made fundamental contributions to the manner in which equatorial modes and convection intertwine. I appreciate the hard and inspirational work Tom Hopson, jun Jian and Kris Shrestha who developed long-horizon prediction schemes for Bangladesh and Pakistan. Also, thanks to Tom, Jun, jun, Bob Grossman, Subbiah-Ji of RIMES and Tom Brennan (of USAID), with whom I shared adventures in South Asia, Bangladesh and Pakistan attempting to implement these forecasting schemes. We may even have actually done something useful!

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 our cramped shared office in Australia. His work has gone onwards to influence climate research globally. He surely has influenced my way of thinking about the role of clouds in global climate. Professor Bin Wang’s support, scientific collaboration, generosity and friendship through the years have remained very important to me. Much of our joint research appears throughout the text. Roger Lukas, my hard-working and dedicated “partner in TOGA COARE crime,” insisted I realize that the tropics must be thought of as a closely coupled ocean–atmosphere system across all time scales. I think his influence permeates much of the text.

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.

It is a pleasure to acknowledge two colleagues who, early in my career, changed the way I think about science. The first was A. J. “Sandy” Troup of Australia, who showed that you could do quiet, personal research with dignity and without the expectation acknowledgement and be successful and influential. He explained the coupled nature of the Southern Oscillation 5–10 years before it became an accepted theory, but received little credit for his publications, externally or internally. Just doing the science was sufficient for him. I met Shri Dev Sikka-ji during my first visit to India in 1976. He remained an influential colleague for the next 40 years. He was a monsoon polymath with extraordinary physical insight and his contributions were rooted in his profound urge to understand the monsoon system fully and make this knowledge useful to society. His enthusiasm and dedication were infectious!

I wish to thank my doctoral advisor Professor N. A. Phillips of Massachusetts Institute of Technology, who patiently introduced me to careful science. In addition, I am indebted for the support I have received from Federal and International organizations, especially from the US National Science Foundation and the late Dr. Jay S. Fein.

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Finally, I would like to thank Judith Curry, my close companion and a supporter of what I have tried to achieve in this text and in so many other things. Her continual support and encouragement is appreciated at a most fundamental level.

I would like to thank my family for their love and for putting up with the long absences due to conferences, seemingly endless committee work, and field expeditions.

Reno, NV Peter J. Webster
September, 2019

Abbreviations

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

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

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
α_v	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 df/dy
β_S	salinity contraction coefficient of sea water
C	Symbolic Coriolis force
C	integrated circulation
c'	vortex tube circulation
C_D	drag coefficient
c_g	wave group speed
$\underset{\sim}{c}_g$	group velocity vector $(c_{gx}\widetilde{i} + c_{gy}\widetilde{j} + c_{gz}\widetilde{k})$
c_{gx}	zonal wave group speed
c_{gy}	meridional wave group speed
C_p	specific heat of air at constant pressure
c_p	wave phase speed $(gH)^{1/2}$
c_{px}	zonal wave phase speed
c_{py}	meridional wave phase speed
c_{gz}	vertical wave group speed
c_{pz}	vertical wave phase speed
$\widetilde{c}$	reduced gravity phase speed $(\widetilde{g}H)^{1/2}$
D	dissipation of kinetic energy
D_e	depth of the ocean Ekman layer
D_o	depth of no ocean motion
D_v	Divergence $(\partial u/\partial x + \partial v/\partial y)$
δ - function	Dirac delta function
δ	increment
E	evaporation rate
$\mathrm{E_K}$	Ekman number
e_v	water vapor partial pressure
e_{sv}	saturated vapor pressure
ε_m	long-wave radiation emissivity
ε	energy density of a wave
η	absolute vorticity $(\zeta + f)$
η_θ	absolute vorticity on an isentropic surface $(\zeta_\theta + f)$
θ	potential temperature
θ_e	equivalent potential temperature
f	vertical component of Coriolis parameter $(2\Omega \sin \varphi)$
$\mathrm{f_r}$	representative frequency used in scaling
F	radiative flux
$\widetilde{F}$	dissipation or frictional force vector
F_B	buoyancy flux
F_O	ocean buoyancy
$\mathrm{F_R}$	Froude number
F_W	surface fresh water flux into the ocean $(E\text{-}P)$
g	gravitational acceleration
$\widetilde{g}$	reduced gravitational acceleration
G	atmospheric scale height (RT/g)

G	scale height (RT/g)
γ_s	dissipation rate
Γ_d	dry adiabatic lapse rate
Γ_s	dry adiabatic lapse rate
Γ^2	wave refractive index
$\overline{\mathrm{H}}$	mean depth of a shallow fluid
$\mathrm{H_S}(y)$	slope of the shallow fluid needed to maintain a geostrophic background flow
$h_B\ (x,y)$	topography of the lower boundary in a shallow fluid
$h\ (x,y)$	perturbation surface displacement in a shallow fluid: equivalent depth
h_s	ocean steric height
$\mathbb{H}_n$	nth order Hermite polynomial
$\underset{\sim}{i}, \underset{\sim}{j}$ and $\underset{\sim}{k}$	Cartesian unit vectors in the x, y and z directions
I_E	emitted terrestrial radiation to space at top of atmosphere
I_S	net surface longwave radiation
$I_{S\downarrow}$	downward longwave radiation at surface
$I_{S\uparrow}$	upward longwave radiation at surface
J_A	advective flux of potential vorticity substance on an isentropic surface
$J_{\dot\theta}$	potential vorticity substance flux on an isentropic surface due to non-adiabatic heating
J_F	potential vorticity substance flux on an isentropic surface due to dissipative processes
J_T	total potential vorticity substance flux on an isentropic surface $(= J_A + J_{\dot\theta} + J_f)$
$J_0(z)$	vertical heating function
k	longitudinal or zonal wave number
K_E	kinetic energy
k_i	general wavenumber in direction "i"
ξ	wave action density
κ	ratio of gas constant and specific heat at constant pressure R/C_p
ln(p)	log pressure
L	lateral scale of a gravity wave
l	latitudinal or meridional wave number
L, D	representative length and height scales used in scaling
L_0	diameter of pond
L_H	surface latent heat flux into the atmosphere
L_P	latent heat release due to precipitation

L_z	vertical scale
$\mathrm{L_E}$	latent heat of evaporation-condensation
$\mathrm{L_F}$	latent heat of fusion
$\mathrm{L_S}$	latent heat of sublimation-deposition
λ	longitude
$\overline{M}_{ie}$	vertically integrated Ekman ocean mass flux in direction *i*.
M_g	geostrophic mass transport in the ocean
δM_g	incremental geostrophic mass transport in the ocean
$\overline{M}_i$	total vertically integrated ocean mass flux in direction *i*.
M	mass of a reservoir of a water substance
M_A	angular momentum
m	vertical wave number
m_o	map scaling factor
m	magnitude of mass source/sink
μ	latitudinal structure function of mass source/sink μ
$\tilde{n}$	normal unit vector
N^2	Brunt-Väisälä frequency
υ	specific volume anomaly
Φ	potential
φ	latitude
ϕ	geopotential
P	Precipitation rate (e.g., mm/ay)
p	pressure
P_m	measure of the persistence of SST
$\mathrm{p}(y), \mathrm{q}(y)$	functions defined in equ. (5.11)
p_s *or* p_0	reference or standard pressure often 1000 hPa
$(P\text{-}E)$	Precipitation rate minus evaporation rate or net fresh water flux at ocean or land surface
ψ_i	radiation penetration depth in ocean
ψ	Stokes streamfunction
$\dot{Q}$	total diabatic heating
Q_S	total heat flux at the surface
Q_T	total columnar heating of an atmospheric or ocean column
Q_{SP}	sensible heat surface cooling of precipitation
q_v	specific humidity
q_{vs}	saturation specific humidity
q_s	potential vorticity substance of an isentropic surface;$q_S = \sigma q$
q_g	geostrophic potential vorticity
q	potential vorticity on an isentropic surface or Ertel's potential vorticity
q_h	potential vorticity in a shallow fluid
q_p	potential vorticity on an isobaric surface
q_s	potential vorticity substance
$\mathbb{R}$	real part of an expansion
r	correlation coefficient
R	specific gas constant
R	Rossby Radius of Deformation
R_C	Radius of curvature
$\mathrm{R_E}$	equatorial Rossby Radius of Deformation
R_d	specific gas constant for dry air
R_s	specific gas constant for moist air
R_E	net radiation at top of atmosphere
$\mathrm{R_E}$	Reynold's Number
$\mathrm{R_i}$	Richardson number
R_{NET}	net radiative flux into an atmospheric or ocean column
$\mathrm{R_o}$	Rossby number
R_S	net surface radiation
R_v	gas constant for water vapor
ρ	density
ρ_0	standard density
ρ_w	density liquid water
ρ_a	air density at ocean surface
S_R	flux of water substance into a reservoir
S_0	solar radiation arriving at Earth: Solar Constant
S	net incoming solar radiation top of atmosphere
S_m	mass source/sink in shallow fluid or time rate of change of mass between isentropes
S_H	surface sensible turbulent heat flux
S_P	sensible heat flux from precipitation
S_S	net surface shortwave radiation
S	static stability
s	salinity
s_0	standard value of salinity
σ_{SB}	Stefan-Boltzman constant
σ	isentropic mass density
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
T_A	average temperature of planetary atmosphere
T_B	infrared cloud brightness temperature
T_o	surface temperature of a planet
T_S	surface temperature
T_{SST}	surface temperature of ocean surface
t	time
τ_i	wind stress component in direction i
$\overline{U}$	background zonal wind
$\overline{U}_{WD}$	magnitude of mean zonal wind in westerly duct
$\overline{U}_{WS}$	basic wind shear between 850 hPa and 250 hPa
U, V, W	representative scales of the zonal, meridional and vertical velocity components used in scaling
u	zonal wind component
u^*	deviation of the zonal velocity component from zonal average
u_e	zonal Ekman current component
u_g	geostrophic zonal wind component
υ	solar radiation absorption coefficient
$\overline{V}$	background meridional wind
$\tilde{V}$	velocity vector
V_ψ	rotational component of velocity
V_χ	divergent component of velocity
$\tilde{V}_g$	vector geostrophic velocity
v	meridional wind component
v_e	meridional Ekman current component
v_g	geostrophic meridional wind component
v_T	measure of the convergence of the trade winds in Pacific Ocean
v^*	deviation of the meridional velocity component from zonal average
$\mathrm{W_p}$	precipitable water in an atmospheric column
w	vertical wind component (dz/dt)
w_Z	dZ/dt: vertical velocity in Z (= $-\overline{\mathrm{G}}\ln(p/p_s)$) coordinates.
w_p	vertical wind component in pressure coordinates (dp/dt)
$\mathrm{w_e}$	Ekman vertical velocity component
Ω	rotation rate of the planet
ϖ	angular velocity
ω	modal frequency
ω_d	Doppler-shifted modal frequency
$\tilde{V}$	Vector velocity with components $u\underset{\sim}{i}, v\underset{\sim}{j}$ and $w\underset{\sim}{k}$
χ	Velocity potential
ζ	horizontal component of relative vorticity ($\partial v/\partial x - \partial u/\partial y$)
ζ_T	total horizontal component of relative vorticity(mean plus perturbation)
y_T	turning latitude
z	height
$\mathrm{z_0}$	reference height in the atmosphere
$\mathrm{z_m}$	height of the Himalayan-Tibetan Plateau
Z	vertical coordinate = $-\overline{\mathrm{G}}\ln(p/p_s)$