

**Development of a Methodology for Probable Maximum Precipitation Estimation
over the American River Watershed Using the WRF Model**

By

ELCIN TAN

B.S. (Istanbul Technical University) 1999

M.S. (Istanbul Technical University) 2001

DISSERTATION

Submitted in partial satisfaction of the requirements for the degree of

DOCTOR OF PHILOSOPHY

in

CIVIL AND ENVIRONMENTAL ENGINEERING

in the

OFFICE OF GRADUATE STUDIES

of the

UNIVERSITY OF CALIFORNIA

DAVIS

Approved:

M. Levent Kavvas, Chair

Timothy R. Ginn

Fabian A. Bombardelli

Committee in Charge

2010

UMI Number: 3404936

All rights reserved

INFORMATION TO ALL USERS

The quality of this reproduction is dependent upon the quality of the copy submitted.

In the unlikely event that the author did not send a complete manuscript and there are missing pages, these will be noted. Also, if material had to be removed, a note will indicate the deletion.



UMI 3404936

Copyright 2010 by ProQuest LLC.

All rights reserved. This edition of the work is protected against unauthorized copying under Title 17, United States Code.



ProQuest LLC
789 East Eisenhower Parkway
P.O. Box 1346
Ann Arbor, MI 48106-1346

Development of a Methodology for Probable Maximum Precipitation Estimation
over the American River Watershed Using the WRF Model

Abstract

A new physically-based methodology for probable maximum precipitation (PMP) estimation is developed over the American River Watershed (ARW) using the Weather Research and Forecast (WRF-ARW) model. A persistent moisture flux convergence pattern, called Pineapple Express, is analyzed for 42 historical extreme precipitation events, and it is found that Pineapple Express causes extreme precipitation over the basin of interest. An average correlation between moisture flux convergence and maximum precipitation is estimated as 0.71 for 42 events. The performance of the WRF model is verified for precipitation by means of calibration and independent validation of the model. The calibration procedure is performed only for the first ranked flood event 1997 case, whereas the WRF model is validated for 42 historical cases. Three nested model domains are set up with horizontal resolutions of 27 km, 9 km, and 3 km over the basin of interest. As a result of Chi-square goodness-of-fit tests, the hypothesis that “the WRF model can be used in the determination of PMP over the ARW for both areal average and point estimates” is accepted at the 5% level of significance. The sensitivities of model physics options on precipitation are determined using 28 microphysics, atmospheric boundary layer, and cumulus parameterization schemes combinations. It is concluded that the best triplet option is Thompson microphysics, Grell 3D ensemble cumulus, and YSU boundary layer (TGY), based on 42 historical cases, and this TGY triplet is used for all analyses of this research.

Four techniques are proposed to evaluate physically possible maximum precipitation using the WRF: 1. Perturbations of atmospheric conditions; 2. Shift in atmospheric conditions; 3. Replacement of atmospheric conditions among historical events; and 4. Thermodynamically possible worst-case scenario creation. Moreover, climate change effect on precipitation is discussed by emphasizing temperature increase in order to determine the physically possible upper limits of precipitation due to climate change. The simulation results indicate that the meridional shift in atmospheric conditions is the optimum method to determine maximum precipitation in consideration of cost and efficiency. Finally, exceedance probability analyses of the model results of 42 historical extreme precipitation events demonstrate that the 72-hr basin averaged probable maximum precipitation is 21.72 inches for the exceedance probability of 0.5 percent. On the other hand, the current operational PMP estimation for the American River Watershed is 28.57 inches as published in the hydrometeorological report no. 59 and a previous PMP value was 31.48 inches as published in the hydrometeorological report no. 36. According to the exceedance probability analyses of this proposed method, the exceedance probabilities of these two estimations correspond to 0.036 percent and 0.011 percent, respectively.

DEDICATION

I dedicate my dissertation to Mustafa Kemal ATATURK

&

to my entire family for happy times I always remember, especially to them who make my life beautiful, livable, and virtuous:

Great Mother	Adalet Atakan
Grand Mother	Ceyhan Andic
Grand Father	Hayrettin Andic
Grand Aunt	Gulgun Atakan
Grand Uncle	Seyhan Atakan
Aunt	Pinar Emiroglu
Uncle I	Ziya Emiroglu
Uncle II	Yavuz Tan
Uncle III	Cetin Tan
Cousin	Evrin Tan
Mother	Bahar Tan
Father	Ali Hasan Tan

My dedication to my father goes twice since he is the only person who continuously believes in me, especially for the times I even doubted myself.

ACKNOWLEDGMENTS

I have completed this dissertation under the supervision of Prof. M. Levent Kavvas to whom I am indebted for providing me all the opportunities during my studies and guiding me with a great deal of patience and devotion.

Prof. Timothy R. Ginn and Asst. Prof. Fabian A. Bombardelli are not only acknowledged for serving in my dissertation and qualifying examination committees, but they are also gratefully appreciated for being an indestructible rocks in my life.

Prof. Carlos Puente and Dr. Z.Q. Chen are acknowledged for serving in my qualifying examination.

There are no words to express my deep gratitude to Prof. H. Nuzhet Dalfes for his sagacious mentorship during the last decade.

I would also like to thank Assoc. Prof. Yurdanur Sezginer Unal and Dr. Baris Onol for their continuous support and encouragement.

I would like to state my appreciation to the staff of the Aeronautics and Astronautics Faculty at Istanbul Technical University who made my life easier. I have been affiliated with the Department of Meteorological Engineering as a research assistant, with a partial financial support during my PhD as a part of the academician training program of Istanbul Technical University.

The staff of the Department of Civil and Environmental Engineering at UC Davis including its Hydrologic Research Laboratory and its Amorochio Hydraulics Laboratory are also appreciated.

I have been financially supported from several projects of California Department of Water Resources, US Bureau of Reclamation, NCAR and NASA.

I would like to thank numerous people who share their knowledge with open source community especially for the WRF, NCL, and R.

I am grateful to my inspirations: Inci Abla, Ulker Serifsoy, Prof. Istemi Unsal, Dr. Peter P. Sullivan, Prof. Fevzi Unal, Asst. Prof. Jeremy Pal, and Dr. Filippo Giorgi.

I would not complete my doctorate studies without my friends who have been with me all the time, no matter what: Bilkay Gulacti, Violet Shu Xu, Aysegul Yelkenci Firat, Deniz Firat, Dr. Regine Scheder, Daniel Nover, Cindy Nover, Bulent Tutkun, Gulcan Ucar Tutkun, Hakan Bagci, Alexander Yuen, Gorkem Gunbas, Ulas Apak, Dr. Baris Caldag, Ines Meireles, Yasemin Yilmaz, Deniz Demirhan Bari, Tamir Kamai, Dr. Bayram Celik, Burak Yikilmaz, Yasemin Polat Yikilmaz, Maya Yikilmaz, Melike Gurbuz, Alya Gurbuz, Akin Gurbuz, Umit Yildiz, Sanjeev K. Jha, Kristin Eastman Reardon, Dr. Sevinc S. Sengor, Ahmet Faruk Ozturk, Baris Ozgun, Dr. Seyda Acar, Asst. Prof. Seda Ersus Bilek, and Kerem Alper.

Finally, I owe thanks to those unnamed persons who made me realize how much I love science/engineering by discriminating against me, misjudging my capacity, pretending to help me, and saying things behind my back to destroy my career.

LIST of TABLES

Table 2.1 The WRF microphysics options (ARW-Version3).....	27
Table 2.2 The WRF cumulus parameterization options (ARW-Version3)	32
Table 2.3 The WRF planetary boundary layer parameterization options (ARW-Version3) ...	37
Table 3.1 The WRF model physics option configurations for calibration purposes.....	54
Table 3.2 72-hour maximum watershed averaged precipitation of the American River Watershed observation vs. the WRF model for validation purposes (USACE, 2005)	55
Table 3.3 Precipitation observation stations	58
Table 3.4 Precipitation observations vs. the WRF precipitation (inches).....	59
Table 3.5 Station based Chi-square goodness-of-fit test.....	61
Table 3.6 SET-I The WRF model physics option configurations- Sensitivity analyses of MP	63
Table 3.7 SET-II The WRF model physics option configurations- Sensitivity analyses of PBL.....	64
Table 3.8 SET-III The WRF model physics option configurations- Sensitivity analyses of CU	64
Table 4.1 The WRF model precipitation versus convergence term of MFC correlations	88
Table 4.2 Minimum and maximum values of relative humidity and wind velocity for 42 extreme precipitation events during a 52-year historical period.....	99
Table 4.3 Moisture and wind maximization combination effect on precipitation for the 1997 flood case	103
Table 4.4 IC only and combined IC+BC effects on precipitation based on wind maximization (1997 event only)	104
Table 4.5 72-hr maximum basin averaged precipitation for replaced events (inches)	106
Table 4.6 72-hr maximum basin averaged precipitation obtained by meridional shifting (inches)	110
Table 4.7 72-hr maximum basin averaged precipitation obtained by meridional shifting for 42 historical events (inches).....	112
Table 4.8 72-hr maximum basin averaged precipitation obtained by zonal shifting (inches)	113
Table 4.9 72-hr maximum basin averaged precipitation obtained by zonal shifting for all 42 historical events (inches).....	115
Table 4.10 72-hr maximum basin-averaged precipitation under the saturated atmosphere (100% RH) conditions	117

Table 4.11 Maximized precipitation for all 42 historical cases (inches)	118
Table 4.12 72-hr maximum basin-averaged precipitable water (inches).....	120
Table 4.13 Climate change effect on maximum precipitation based on the 1997 case	122
Table 4.14 Precipitation maximization methods and their basin averaged values for the 1997 historical event (11.48 inches).....	124
Table 5.1 The validity of the main assumption of the traditional PMP methods	130
Table 5.2 Statistical distributions and their parameters for historical events.....	148
Table 5.3 Precipitation for various degrees of exceedance probability (inches)	154
Table 6.1 Physically possible maximum Precipitation comparisons with Traditional PMP obtained from HMR59 (inches)	158

LIST of FIGURES

Figure 2.1 Horizontal and vertical grids of the WRF (ARW-Version3)	24
Figure 2.2 The WRF-ARW model domain configuration.....	43
Figure 3.1 GOES Visible 3:00 PM PST Tuesday Dec 31, 1996	47
Figure 3.2 The synoptic pattern of the 1997 event (NOAA, 1997).....	48
Figure 3.3 300 mb wind vector climatology for December 26 - January 3 (1968-1996) (NOAA, 1997)	48
Figure 3.4 300 mb wind vector analysis for the 1997 event (NOAA, 1997).....	49
Figure 3.5 Composite mean precipitable water on January 1, 1997 (NOAA, 1997).....	50
Figure 3.6 Water vapor mixing ratio results of the WRF at Eta Level 11 on January 1, 1997	50
Figure 3.7 The map of the American River Watershed and precipitation stations.....	58
Figure 3.8 The WRF Physics option sensitivities to precipitation.....	66
Figure 4.1 Pineapple express events that caused extreme precipitation and flood.....	72
Figure 4.2 Pineapple express events that did not cause extreme precipitation and flood.....	80
Figure 4.3 Pineapple express effect on maximum precipitation of January 97.....	83
Figure 4.4 Horizontal moisture flux profiles for 42 historical cases	90
Figure 4.5 Maximum precipitation change with moisture only for the 1997 case	100
Figure 4.6 Maximum precipitation change with wind speed only for the 1997 case	102
Figure 4.7 Combined moisture and wind perturbation effect on precipitation for the 1997 flood case	103
Figure 4.8 IC only and combined IC+BC effects on precipitation for the 1997 case only ..	105
Figure 4.9 The WRF precipitation results of replaced events.....	107
Figure 4.10 Meridionally shifted maximum precipitation (inches)	109
Figure 4.11 Zonally shifted maximum precipitation (inches)	113
Figure 4.12 72-hr maximum basin-averaged precipitation change with the increase in temperature.....	122
Figure 5.1 Maximum observed point rainfalls as a function of duration. (Courtesy of John Vogel, National Weather Service [NRC94])	125

Figure 5.2 Precipitable Water vs. Precipitation (inches).....	128
Figure 5.3 Time series of the ratios of precipitation to precipitable water.....	131
Figure 5.4 Time series of the modeled and approximated PMP	131
Figure 5.5 Relative frequency histogram of 72-hr maximum basin averaged precipitation for the historical storms at the ARW	133
Figure 5.6 Exceedance probability distribution of 72-hr maximum basin averaged precipitation for historical storms at the ARW.....	133
Figure 5.7 Gamma distribution fitted to the relative frequency histogram of 72-hr maximum basin averaged precipitation for the historical storms at the ARW	134
Figure 5.8 Q-Q plot for historical storms at the ARW	134
Figure 5.9 Relative frequency histogram of 72-hr maximum basin averaged precipitation for the historical storms at the ARW after a 2 degrees shift from N to S	135
Figure 5.10 Exceedance probability distribution of 72-hr maximum basin averaged precipitation for historical storms at the ARW after a 2 degrees N to S shift.....	135
Figure 5.11 Gamma distribution fitted to the relative frequency histogram of 72-hr maximum basin averaged precipitation for the historical storms at the ARW after a 2 degrees N to S shift	136
Figure 5.12 Q-Q plot for historical storms after a 2 degrees N to S shift	136
Figure 5.13 Relative frequency histogram of 72-hr maximum basin averaged precipitation for the historical storms at the ARW after a 4 degrees shift from N to S	137
Figure 5.14 Exceedance probability distribution of 72-hr maximum basin averaged precipitation for historical storms at the ARW after a 4 degrees N to S shift.....	137
Figure 5.15 Gamma distribution fitted to the relative frequency histogram of 72-hr maximum basin averaged precipitation for the historical storms at the ARW after a 4 degrees N to S shift	138
Figure 5.16 Q-Q plot for historical storms after a 4 degrees N to S shift	138
Figure 5.17 Relative frequency histogram of 72-hr maximum basin averaged precipitation for the historical storms at the ARW after a 6 degrees shift from N to S shift	139
Figure 5.18 Exceedance probability distribution of 72-hr maximum basin averaged precipitation for historical storms at the ARW after a 6 degrees N to S shift.....	139
Figure 5.19 Weibull distribution fitted to the relative frequency histogram of 72-hr maximum basin averaged precipitation for the historical storms at the ARW after a 6 degrees N to S shift	140
Figure 5.20 Q-Q plot for historical storms after a 6 degrees N to S shift	140

Figure 5.21 Relative frequency histogram of 72-hr maximum basin averaged precipitation for the historical storms at the ARW after a 6 degrees shift from W to E.....	141
Figure 5.22 Exceedance probability distribution of 72-hr maximum basin averaged precipitation for historical storms at the ARW after a 6 degrees W to E shift	141
Figure 5.23 Gamma distribution fitted to the relative frequency histogram of 72-hr maximum basin averaged precipitation for the historical storms at the ARW after a 6 degrees W to E shift	142
Figure 5.24 Q-Q plot for historical storms after a 6 degrees W to E shift	142
Figure 5.25 Relative frequency histogram of 72-hr maximum basin averaged precipitation for the historical storms at the ARW after a 100% relative humidity adjustment	143
Figure 5.26 Exceedance Probability Distribution of 72-hr maximum basin averaged precipitation for historical storms at the ARW after a 100% RH adjustment.....	143
Figure 5.27 Weibull distribution fitted to the relative frequency histogram of 72-hr maximum basin averaged precipitation for the historical storms at the ARW after a 100% RH adjustment	144
Figure 5.28 Q-Q plot from historical storms after a 100% RH adjustment	144
Figure 5.29 Relative frequency histogram of 72-hr maximum basin averaged precipitation for the historical storms at the ARW corresponding to the WRF model-calculated precipitable water.....	145
Figure 5.30 Exceedance Probability Distribution of 72-hr maximum basin averaged precipitation for historical storms at the ARW corresponding to the WRF model-calculated precipitable water.....	145
Figure 5.31 Gamma distribution fitted to the relative frequency histogram of 72-hr maximum basin averaged precipitation for the historical storms at the ARW corresponding to the WRF model-calculated precipitable water.....	146
Figure 5.32 Q-Q plot from historical storms corresponding to precipitable water	146
Figure 5.33 Exceedance probability of the precipitation ratio- historical over 100% RH....	151
Figure 5.34 Exceedance probability of the precipitation ratio- historical over PW	151
Figure 5.35 Exceedance probability of 72-hr maximum basin averaged precipitation for the historical storms at the ARW	153
Figure 5.36 Exceedance probabilities of maximized historical events.....	153

NOMENCLATURE

$\alpha_d = 1/\rho_d$	Specific volume for dry air	$[1/kgm^{-3}]$
c_p	Specific heat capacity at constant pressure	$[J\ kg^{-1}\ K^{-1}]$
c_s	Specific heat capacity of soil	$[J\ kg^{-1}\ K^{-1}]$
c_v	Specific heat capacity at constant volume	$[J\ kg^{-1}\ K^{-1}]$
C	Convergence Influenced PMP	[inches]
η	Vertical Coordinate Terrain Following Mass	[1]
$\phi = gz$	Geopotential	$[m^2s^{-2}]$
F	Heat Flux	$[W\ m^{-2}]$
F_U, F_V, F_W	Forcing terms of conservation of momentum	$[N]$
F_θ	Forcing term of conservation of energy	$[kg\ K\ s^{-1}]$
F_{Q_m}	Forcing term of conservation of moisture	$[kg^2\ kg^{-1}s^{-1}]$
g	Gravitational Acceleration	$[ms^{-2}]$
$\gamma = c_p/c_v = 1.4$	Ratio of the heat capacities	[1]
K	Empirically determined enveloping constant	[1]
K	Thermal diffusivity of soil	$[m^2s^{-1}]$
$m = v, c, r, i, g, s$	hydrometeors: water vapor, cloud vapor, rain, cloud ice, graupel, and snow, respectively.	
$\mu_d = p_{dhs} - p_{dht}$	Mass of dry air	[mass per unit area]
$\omega = \dot{\eta}$	Contravariant Vertical Velocity	$[m\ s^{-1}]$

p	Pressure	[hPa]
p_0	Reference Pressure	[hPa]
p_{dh}	Hydrostatic component of the pressure for dry atmosphere	[hPa]
p_{dhs}	Surface p_{dh}	[hPa]
p_{dht}	Top p_{dh}	[hPa]
P	Precipitation	[inches]
$P_{\max}$	Maximum Precipitation	[inches]
PMP	Probable Maximum Precipitation	[inches]
$PW = \frac{1}{\rho_w g} \int_0^{p_0} q dp$	Precipitable Water	[kg m ⁻²] or [in]
q	Specific Humidity	[kg kg ⁻¹]
q	Mixing Ratio	[mass per mass of dry air]
Q	Heating Rate	[Ks ⁻¹]
$R = c_p - c_v$	Gas Constant	[J deg ⁻¹ kg ⁻¹]
R_d	Gas Constant for dry air	[J deg ⁻¹ kg ⁻¹]
ρ_s	Soil Density	[kg m ⁻³]
ρ_w	Density of water	[kg m ⁻³]
$S_n; \sigma$	Standard Deviation	
θ	Potential Temperature	[K]
T	Temperature	[K]
T	Total PMP	[inches]
$\mathbf{v} = (u; v; w)$	Covariant Velocities	[m s ⁻¹]

$\mathbf{V} = \mu_d \mathbf{v} = (U; V; W)$	Velocities	$[\text{m s}^{-1}]$
w	Mixing Ratio	$[\text{kg kg}^{-1}]$
w_{max}	Maximum Mixing Ratio	$[\text{kg kg}^{-1}]$
$\overline{X}$	Mean of the maximum observed daily precipitation	$[\text{inches}]$
X_{max}	24-hr PMP	$[\text{inches}]$

ABBREVIATIONS

ACM2	Asymmetrical Convective Model Version 2
AFWA	Air Force Weather Agency
AMS	American Meteorological Society
AR	American River
ARs	Atmospheric Rivers
ARW	American River Watershed
ARW	Advanced Research WRF
BC	Boundary Condition
BMJ	Betts-Miller-Janjic CU scheme
CBL	Convective Boundary Layer
CAPE	Convective Available Potential Energy
CCDF	Complementart Cumulative Distribution Function
CDEC	California Data Exchange Center
CDF	Cumulative Distribution Function
CISL	Computational and Information Systems Laboratory at NCAR
CMBL	Cumulus, Microphysics and Boundary Layer
COMMAS	Collaborative Model for Multiscale Atmospheric Simulation
CU	Cumulus Parameterization
CV	Calibration and Validation
DAD	Depth-Area-Duration
DTC	Developmental Testbed Center
E	East direction
EGCP	Eta Grid-scale Cloud and Precipitation
ENSO	El-Nino Southern Oscillation
ETA	Eta Model
FAA	Federal Aviation Administration
FSL	Forecast Systems Laboratory
GCE	Goddard Cumulus Ensemble
GOES	Geostationary Operational Environmental Satellites
HMR36	Hydro-Meteorological Report No.36
HMR57	Hydro-Meteorological Report No.57

HMR58	Hydro-Meteorological Report No.58
HMR59	Hydro-Meteorological Report No.59
IC	Initial Condition
IPCC	Intergovernmental Panel on Climate Change
MFC	Moisture Flux Convergence
MJO	Madden Jullian Oscillation
MM5	PSU/NCAR mesoscale model
MMM	Mesoscale and Microscale Meteorology Division of NCAR
MOD	Model
MP	Maximum Precipitation
MP	Microphysics Parameterization
MPP	Maximum Possible Precipitation
MRF	Medium Range Forecast Model PBL
MYJ	Mellor-Yamada-Janjic PBL scheme
N	North direction
NCAR	National Center of Atmospheric Research
NCEP	National Centers for Environmental Prediction
NCL	NCAR Command Language
NH	Northern Hemisphere
NMM	Nonhydrostatic Mesoscale Model
NNRP	NCEP/NCAR Global Reanalysis Products
NOAA	National Oceanic and Atmospheric Administration
NRC	National Research Center
NS	PE shifting from the North to the South
NWP	Numerical Weather Prediction
OBS	Observation
OLR	Outgoing Longwave Radiation
PBL	Planetary Boundary Layer
PE	Pineapple Express
PEF	Possible Extreme Flood
PEP	Possible Extreme Precipitation
PMF	Probable Maximum Flood
PMP	Probable Maximum Precipitation
PNA	Pacific North American Pattern

PNP	Persistent North Pacific Circulation
PRISM	Parameter-elevation Regressions on Independent Slopes Model Data
PSU	Penn State University
PW	Precipitable Water
QE	Qualifying Examination
QPF	Quantitative Precipitation Forecast
R	The Statistical Environment and Language R
RDA	Research Data Archive
RH	Relative Humidity
RRTM	Rapid Radiative Transfer Model
RUC	Rapid Update Cycle Model
S	South direction
STA	Statistic: Individual Scale Deviation Value
TGY	Thompson-Grell 3D-YSU scheme triplet
TKE	Turbulent Kinetic Energy
USACE	United States Army Corps of Engineers
USGS	United States Geological Survey
W	West direction
WE	PE shifting from the West to the East
WMO	World Meteorological Organization
WRF	Weather Research Forecast Model
WSF	The WRF Software Framework
WSM3	The WRF Single Moment 3-Class MP Scheme
WSM5	The WRF Single Moment 5-Class MP Scheme
WSM6	The WRF Single Moment 6-Class MP Scheme
WV	Water Vapor
YSU-PBL	Yonsei University PBL

TABLE of CONTENTS

Abstract.....	ii
DEDICATION.....	iv
ACKNOWLEDGEMENTS.....	v
LIST of TABLES	vi
LIST of FIGURES	viii
NOMENCLATURE.....	xi
ABBREVIATIONS	xiv
TABLE of CONTENTS	xvii
CHAPTER I- Introduction	1
1.1 Motivation	1
1.2 Literature Review	2
1.3 Research Objectives.....	13
1.4 Methodology	15
1.5 Scientific Value.....	16
1.6 Outline	17
CHAPTER II- Methodology	19
2.1 The Weather Research and Forecasting (WRF) model description	19
2.2 Cloud Microphysics Schemes	26
2.2.1 Kessler scheme	27
2.2.2 Purdue Lin scheme	27
2.2.3 The WRF Single-Moment 3-class (WSM3) scheme.....	28
2.2.4 The WRF Single-Moment 5-class (WSM5) scheme.....	28
2.2.5 The WRF Single-Moment 6-class (WSM6) scheme.....	29
2.2.6 Eta Grid-scale Cloud and Precipitation (2001) scheme- EGCP01.....	29
2.2.7 Thompson et al. scheme.....	29
2.2.8 Goddard Cumulus Ensemble Model (GCE) scheme	30
2.2.9 Morrison scheme	31
2.3 Cumulus Parameterization.....	31
2.3.1 Kain-Fritsch scheme	32
2.3.2 Betts-Miller-Janjic scheme.....	33
2.3.3 Grell-Devenyi ensemble scheme	33
2.3.4 Grell-3D ensemble scheme.....	34

2.4 Planetary Boundary Layer (PBL) Parameterization	34
2.4.1 Medium Range Forecast Model (MRF) PBL.....	37
2.4.2 Yonsei University (YSU) PBL.....	37
2.4.3 Mellor-Yamada-Janjic (MYJ) PBL.....	38
2.4.4 Asymmetrical Convective Model Version 2 (Pleim) PBL-(ACM2)	38
2.5 Radiation Schemes	39
2.6 Land Surface Schemes	40
2.7 Model Configuration	42
 Chapter III- Calibration and Validation of the WRF model with historical events	44
3.1 Introduction	44
3.2 Historical Events	44
3.2.1 Pineapple Express.....	46
3.3 Data	51
3.3.1 Model Data.....	51
3.3.2 Observation Data.....	51
3.4 Calibration and Validation	52
3.5 Sensitivity Analysis	62
3.6 Chapter Conclusions	67
 Chapter IV- Extreme Precipitation Estimation	69
4.1 Pineapple Express Effect	70
4.1.1 Direction, magnitude, and duration of the Pineapple Express	81
4.2 Moisture Flux Convergence (MFC).....	84
4.2.1 Theory of MFC.....	84
4.2.2 Modeling of MFC.....	87
4.3 Precipitation Maximization Methods	97
4.3.1 Perturbations of Atmospheric Conditions	98
4.3.1.1 Moisture Perturbation Effect.....	98
4.3.1.2 Wind Perturbation Effect.....	101
4.3.1.3 Combined Moisture and Wind Perturbation Effect	102
4.3.1.4 Perturbations in Initial and Boundary Conditions	104
4.3.2 Replacement of atmospheric conditions with respect to land conditions	106
4.3.3 Shift in atmospheric conditions	108
4.3.4 Thermodynamically possible worst-case scenario creation	116
4.4 Climate Change Effect on Precipitation of the American River Watershed.....	120

4.4.1 Effect of Temperature Change	121
4.5 Chapter Conclusions.....	123
Chapter V- Results and Discussions	125
Chapter VI- Summary and Conclusions	155
6.1 Future Perspectives	161
Appendix I	162
Bibliography	164

CHAPTER I

Introduction

1.1 Motivation

To a society in a particular geographical region, dam failure is classified as one of many major potential hazards such as flood, levee failure, ground water recharge, disease transmission, fish survival that cause high losses, although their probability of occurrence is fairly low. According to the National Research Council (NRC), 26 percent of reported dam failures that occurred in the US between 1900 and 1979, are due to over-topping which represents about 13 percent of all incidents. The principal reason for over-topping is the inadequate spillway capacity for these incidents [NRC, 1983]. A spillway design is based on either the estimation of a probable maximum precipitation (PMP) directly, or the estimation of probable maximum flood (PMF) which is derived from PMP. Therefore, the accurate estimation of PMP plays a significant role in the design of dams and in dam failure reduction.

There are several limitations in the current PMP methodology that reveal the need for a more accurate methodology. The original definition of PMP by the American Meteorological Society (AMS) was “the greatest depth of precipitation for a given duration meteorologically possible for a given basin at a particular time of year, with no allowance made for long-term climatic trends” [AMS, 1959]. This definition of PMP was changed in 1982 as “Theoretically, the greatest depth of precipitation for a given duration that is physically possible over a given size storm area at a particular geographical location at a certain time of year” [Hansen, 1987]. This revision in the PMP definition was “Due to the fact that knowledge of storm mechanisms and their precipitation-producing efficiency were

inadequate to permit precise evaluation of limiting values of extreme precipitation. Therefore PMP estimates were considered as approximations” [WMO, 1986]. PMP estimates are still considered as approximations [Corrigan *et al.*, 1999 (HMR59, hereafter)] since they are still being used in operational hydrology as defined in 1982 although our knowledge about storm characteristics and their precipitation-producing efficiencies has advanced significantly in terms of making accurate assessments on extreme precipitation.

The second limitation is that a PMP value needs to be updated each time a new major storm occurs since the PMP constants are determined with respect to the last big storm over a specified watershed. On the other hand, from its definition, PMP has been treated as a theoretical value that was not expected to occur. Hence, the current approach does not approximate an upper limit for the precipitation; it only estimates a precipitation value that is higher than what has occurred before.

The third limitation, which is related to the first one, is that the current methodology is not physically based. This is emphasized in Hydro-Meteorological Report 57 as “while moisture is indeed maximized, numerous other factors are involved at a lesser level to effectively control unreasonable compounding of extremes” [Hansen *et al.*, 1994 (HMR57, Hereafter)]. Other possible shortcomings of the traditional method are going to be discussed in the conclusion chapter.

For these reasons, an operational and physically-based methodology that estimates an optimum PMP value, is needed to obtain accurate results that can supersede the current one.

1.2 Literature Review

Operationally used Probable Maximum Precipitation (PMP) estimation methods can be classified according to their historical periods. Estimation of spillway design floods has

initially been performed according to the judgment of the design engineer. This period is called the early period [Myers, 1967]. Following period is the regional discharge period where design floods were determined based on Fuller's work [Fuller, 1914], on area-related envelope formulae, and on statistical frequency analyses. The third period was called the storm transposition period, since design floods were calculated by using the storm transposition method [Myers, 1967].

Design flood studies have become popular since 1930's with the increasing dam and levee constructions as an act of United States Government against the great economic depression. The PMP estimations were started soon after [Myers, 1967]. In this PMP period, the physical limiting factors on precipitation rate were classified to setup a method for PMP calculations as follows: humidity concentration that flows through the basin, wind rate that brings humidity to the basin, and water vapor (WV) that can be precipitated over the basin [Showalter and Solot, 1942]. In this dissertation, similar factors are going to be investigated for setting up a new method.

The first limiting factor on precipitation, humidity that flows through the basin is associated with the maximum moisture in our study. Total specific humidity as a function of pressure in a unit atmospheric column, the so-called precipitable water (PW) is the best indicator for the evaluation of atmospheric moisture. During the time when PMP estimations started, precipitable water could not be calculated by direct measurements of specific humidity. So studies suggested estimating precipitable water using the surface dew point temperatures as a measure of atmospheric moisture content [Myers, 1967]. This approach to estimating PW was a very coarse approximation. Since we can measure and model atmospheric moisture content with current technology, there is no further need to make this assumption. Yet, this assumption is still being used in the current PMP method.

The second factor, the rate of wind that brings humidity to the basin is connected to wind maximization study of this dissertation. As we will discuss later, maximum wind speed and moisture are used to determine moisture flux convergence, which is a measure of precipitation. In traditional PMP studies, moisture convergence is neither calculated nor measured. Instead, being a coarse approximation, storm adjustment technique is used to take into account the convergence [Myers, 1967]. In this study, modeling of the maximum horizontal convergence is going to be proposed in order to obtain accurate estimations for PMP.

The last limiting factor, the water vapor (WV) that can be precipitated over a basin, is nearly analogous to cumulus parameterization part of a numerical modeling approach. In the traditional method a quite primitive cloud model was developed by assuming that inflow occurs in the lower third of a cloud, outflow occurs in the upper third, and the middle third experiences only the associated vertical wind and moisture motion. Maximum height of the cloud was assumed to extend to the tropopause for the major storms. It was also assumed that the maximum cloud height increased with temperature. The precipitation was assumed to increase by about 9 percent for each 1°C increase in temperature [Myers, 1967]. As will be mentioned later in the cumulus parameterization section of the model, inflows and outflows do not necessarily occur in the assumed levels. Moreover, there are several parameters that are not taken into account, such as updrafts and downdrafts. In the modeling approach presented here, quite sophisticated cloud models are used. Moreover, these cloud models are used for determining large-scale convective systems which are associated with the wet events in California (Mo and Higgins, 1998b) . For smaller scales, microphysical properties of clouds should be considered. None of the PMP procedures takes into account these processes. Therefore, the numerical weather prediction (NWP) modeling approach is

proposed to solve cloud physics in detail.

The current PMP estimations for California are based on Hydrometeorological Report No.58 (HMR58) [*Corrigan et al.*, 1998] and HMR59 that were superseded by Hydrometeorological Report No.36 (HMR36) [*U.S. Weather Bureau*, 1969; *U.S. Weather Bureau*, 1961] in 1998-1999. The main methodological difference between HMR59 and HMR36 is that the depth-area-duration (DAD) relations were determined based on storm-based relations in HMR59. Meanwhile, DADs were calculated by using a primitive mass-conservation model that was based on the physical limiting factors, as explained in the PMP period section [*Myers*, 1967]. The current operational PMP is estimated primarily from historical extreme storm events over a specified region and nearby states with similar climatic regimes. This approach requires that PMP estimates have to be updated when new major storms occur.

In general there are four different types of precipitation: 1. Frontal, 2. Convective, 3. Orographic and 4. Tropical that need to be assessed for reliable PMP calculations rather than two precipitation types as in traditional PMP methods. Moreover, combinations of those all four types of precipitation need to be determined for the major storm occurrences for a specified region instead of isolated storm considerations. For conventional PMP estimates, California is divided into several regions in order to handle orographic influences, and the transposition of the storms is adjusted by appropriate orographic influence factors. Yet, the precipitation depth, duration, and area are dependent upon orographic influences, which should be considered as a part of the storm mechanism. Traditional PMP estimates have been separated as general and local PMP estimates. Precipitation from local storms was differentiated from general-storm rainfall. General-storm PMP estimates were developed using the storm separation or envelopment technique, which provides a way of moisture

maximization and transposing of storms by separating the dynamically forced precipitation from the orographically-forced precipitation. In these storms, precipitation is divided into convergence influenced (non-terrain) and orographic (terrain-influenced) components, which correspond to general storm PMP and local PMP estimates, respectively. The orographic component of the storm (T/C) is factorized by the ratio of total PMP (T) to convergence (C) influenced (general storm) PMP, where total PMP is determined from the 100-year, 24-hour storm maps of NOAA Atlas-2 [WMO, 1986; HMR58; HMR59].

Several studies have been conducted to improve the accuracy of the current operational method for various locations. It should be noted that the PMP results of a location may not be representative for any other location unless they both are affected from the same weather system. For instance, it was found that pseudoadiabatic assumption overestimates PMP by about 6.9% on average for Chicago area [Chen and Bradley, 2006], which needs to be evaluated further for California. On the other hand, it is important to note that the pseudoadiabatic assumption is misused in PMP studies. In atmospheric science, pseudoadiabatic assumption states that all condensed water is immediately removed from an air parcel. Such a process is adiabatic in the sense that the heating rate, $Q = 0$, but the mass of water in the parcel is not constant [Bohren and Albrecht, 1998]. On the other hand, the pseudoadiabatic chart, which is also known as Skew-T Log-P diagram, is the graphical solution to the Poisson's equation:

$$\theta = T \left(\frac{p_0}{p} \right)^{R/c_p} \quad (1.1)$$

For dry air, $R = R_d = 287 J \deg^{-1} kg^{-1}$ and $c_p = 1004 J \deg^{-1} kg^{-1}$; therefore, $R/c_p = 0.286$.

A graphical form of the Equation 1.1 can be written as,

$$T = (const)\theta p^{0.286} \quad (1.2)$$

In the pseudoadiabatic chart, Appendix I, each value of the potential temperature, θ , represents a dry adiabat which is defined by a straight line with a particular slope which passes through the point $p=0$ and $T=0$ [Wallace and Hobbs, 2006]. Similarly, pseudoadiabats, and saturation mixing ratio lines are added to pseudoadiabatic chart for saturated air.

In the current operational PMP estimations, maximum precipitation is estimated using the formula,

$$P_{\max} = \frac{w_{\max}}{w} \times P \quad (1.3)$$

where $P_{\max}$ is probable maximum precipitation, P is observed rainfall, w is precipitable water, and $w_{\max}$ is the maximized precipitable water as given by the maximum 24-hour persisting dew points [Wiesner, 1970; Abbs, 1999]. Unfortunately, there is another misuse in the terminology in that $w_{\max}$ is not precipitable water but is a mixing ratio that is obtained from the maximum 24-hour persisting dew points using the pseudoadiabatic chart. On the other hand, w is obtained from the actual dew point using the same chart. Actually, precipitable water (PW) is defined as the vertical integration of specific humidity as a function of pressure,

$$PW = \frac{1}{\rho_w g} \int_0^{p_0} q dp \quad (1.4)$$

where specific humidity, q , can be interchangeably used with mixing ratio, w . From the above, it follows that the traditional method does not consider the moisture content of the whole atmospheric column. It only takes into account surface moisture content of the maximization of precipitation. In other words, the ratio of the surface mixing ratios do not necessarily equate to the ratios of precipitable water. As such, it is surprising that *Chen and Bradley* found that pseudoadiabatic assumption overestimates PMP [2006], since the maximization factor should be small when only surface moisture content is used. On the other hand, this might explain why PMP values are exceeded in some regions each time a new storm occurs and why these values are too high for some other regions.

From another perspective, the maximum 24-hr persisting dew point temperature usage is also problematic, since the surface dew point temperature changes very dramatically with time, especially diurnally. Therefore, persisting dew point temperature assumption may not be valid. In the new method, presented here, these assumptions are eliminated, especially since atmospheric moisture tendencies are simulated in 3D.

Other limitations of the current method may be addressed using the storm catalog method. One is that PMP is too high for Chicago area and the other is that the determination of the mean moisture availability is difficult if the storm has multiple rain periods. The most obvious constraint found in this study is that the moisture maximization method violates the physical rule since the dew temperature profile cannot be greater than the temperature profile [*Chen and Bradley*, 2007]. It is pointed out that no estimates of the PMP exist for small areas such as armored slopes, and for very short durations [*Codell*, 1986;

Hua et al., 2006]. For such cases one day PMP estimations are performed [*Rakhecha and Clark*, 1999]. It is shown that for short durations and small areas, PMP estimates are exceeded by 29% for Australian extraordinary short-duration heavy rainfall [*Shepherd and Colquhoun*, 1985].

In practice, the above-mentioned studies are valuable attempts for tuning the current method. They are also important indicators that the current PMP estimations need to be improved. However, the results of these estimations may never be as accurate as the results of the numerical atmospheric models.

In addition to the operational storm-based and moisture convergence approaches there are several non-operational PMP estimation techniques that can be classified as i) statistical approach, and ii) numerical weather prediction modeling approach.

Numerical Weather Modeling approach can be seen as an improvement to the moisture convergence approach, although it is not operational yet. The approach, proposed in this research, can be assessed as a combination of storm-based, moisture-convergence, and numerical weather prediction modeling approaches.

In the statistical approach, one practice is to perform DAD analysis based on rainfall data [*Morgan*, 1914; *Corps of Eng.*, 1945; *Miami Con. Dist.*, 1936]. One can argue that this method does not work for the places with no rainfall data. Therefore, the users of this method apply extrapolation methods. Analogous to Fuller's work [*Myers*, 1967], the “state-of-the-art” practice is to calculate PMP based on a generalized frequency equation [*Hershfield*, 1961]:

$$X_{\max} = \bar{X} + KS_n \quad (1.2)$$

$X_{\max}$ is the 24-hr PMP at a given observing point; $\bar{X}$ is the mean of the maximum observed daily precipitation; S_n is the standard deviation of this time series; and the constant K is determined empirically by an enveloping process. Hershfield [1961] found $K=15$ for the United States based on 2645 station records. It should be noted that PMP is highly dependent upon location and therefore the 15 standard deviations may not be representative for some locations. There are numerous applications of the statistical approach for different locations [Campos-Aranda, 1998; Clark, 2002, 2003; Clark and Rakhecha, 2002; Clark, 1967; Desa and Rakhecha, 2007; Dhar and Kamte, 1969, 1971; Dhar and Nandargi, 1993a, 1993b; Dhar et al., 1981; Dhar et al., 1982; Ghabraman, 2008; Hansen, 1975; Jeevarathnam and Jayakumar, 1981; Nobilis et al., 1991; Rezacova et al., 2005] using different techniques [Casas et al., 2008; Douglas and Barros, 2003, 2004; Eliasson, 1997; Kennedy and Hart, 1984; Koutsoyiannis, 1999, 2004a, 2004b; Koutsoyiannis and Baloutsos, 2000].

There are also studies that used storm-based and moisture convergence approaches to determine PMP for different locations [Ding et al., 1986; Kennedy and Hart, 1984; Kulkarni and Nandargi, 1996; Levenson, 1986; Piper et al., 1994; Rakhecha and Kennedy, 1985; Rakhecha and Kulkarni, 1993; Rakhecha and Soman, 1994; Rakhecha and Clark, 2000; Rakhecha et al., 1992a, 1992b; Rakhecha et al., 1995a; Rakhecha et al., 1995b; Schreiner, 1978; Sharma et al., 1988; Singh et al., 1992; Svensson and Rakhecha, 1998; Thompson, 2003; Wang, 1984; Wiesner, 1970; Zhan and Zou, 1986; Zhan and Zhou, 1984].

Applications of numerical weather prediction models to PMP estimation are limited. MM5 was used for a heavy rainfall event that occurred in Kansas-Oklahoma border and it was suggested that the mesoscale models can be useful tools for the assessment of extreme rainfall producing storms in small areas and during short time periods [Zhao et al., 1997].

Four extreme events in Australia were modeled by using RAMS regional atmospheric model to investigate the assumptions used in the PMP estimations. It was suggested that despite the efficiencies found in that study, no operational replacement was possible for the current PMP [Abbs, 1999]. Another modeling-based methodology [Cotton *et al.*, 2002] for determining extreme precipitation potential was performed for Colorado by using a convective-storm-resolving mesoscale model (RAMS). Although the precipitation amounts were obtained by the model for six extreme precipitation events, Hershfield's (1965) PMP technique was used with some modifications [Cotton *et al.*, 2002]. Chen [2005] also suggested that mesoscale models could be used in a limited way to improve traditional PMP results. The method, proposed in this research, is different than the mentioned previous efforts in that precipitation maximization techniques are developed using an atmospheric model.

Traditional PMP calculations depending on geographical formation of a basin. On the other hand, the determination of the persistent weather systems and their interactions for specific locations is also crucial. Since our research is focused on the American River Watershed (ARW), we need to determine weather systems that cause extreme precipitation in this domain of interest. The identification of the extreme precipitation mechanisms for our domain requires much effort for several reasons, one of which is the scale problem that multiple timescales are involved in the system. 52 years of precipitation analysis was performed over the ARW. It was found that annual maximum precipitation occurs between October and April, which corresponds to the most active storm tracks in the North Pacific. Associated with extratropical cyclone activities [Rafael and Mills, 1996], major floods in California are caused by the "Pineapple Express" or atmospheric rivers (ARs), which describes a path of an extensive amount of moisture that traverses over Hawaiian Islands to enter California. This weather system is also called as TEREK, for "Truly Extraordinary

Rainfall Event in California“ [*Baker and Estes*, 1994]. These events might be associated with persistent atmospheric circulation anomaly patterns, one of which occurs in the North Pacific to the South of the Aleutians [*Dole and Gordon*, 1983]. The Pacific decadal timescale variations are linked to recent changes in frequency and intensity of El Niño versus La Niña events. It was also shown that the Aleutian Low pressure system, which is another important weather system in the pineapple express determination, shifts according to the decadal atmosphere-ocean variations [*Trenberth and Hurrell*, 1994]. Extreme precipitation events might also be related to a major teleconnection pattern, called Pacific North American pattern (PNA), which occurs in the Northern Hemisphere winter and is indicated by the mid-tropospheric geopotential height fields [*Wallace and Gutzler*, 1981]. Being a climate-scale phenomenon, El-Niño Southern Oscillation (ENSO) is connected to precipitation variability in North America [*Ropelewski and Halpert*, 1986; *Schonher and Nicholson*, 1989; *Cayan and Peterson*, 1989; *Cayan and Redmond*, 1994; *Cayan et al.*, 1999; *Kahya and Dracup*, 1994; *Mo and Higgins*, 1998a; *Dettinger et al.*, 1998]. It is shown that the extreme precipitation events occur at all phases of the ENSO cycle, but the largest fraction of these events occur during the neutral winters just prior to the onset of El-Niño [*Higgins et al.*, 2000].

Moreover, it was shown that there is a link between persistent North Pacific (PNP) circulation anomalies and tropical interseasonal oscillations in Northern Hemisphere (NH) winter that might explain the extension in Pacific jet [*Higgins and Mo*, 1997]. This extension generally leads to the supply of extensive amount of moisture to the West coast of the U.S. On the other hand, fluctuations in the Pacific jet are associated with 28-72 day planetary-scale oscillations of outgoing longwave radiation OLR [*Weickman et. al*, 1985]. An association was found from the 36-40 day oscillatory modes of OLR [*Mo*, 1999] that California rainfall might be related to the 40-50 day oscillation, the so-called Madden-Julian Oscillation (MJO),

that is the result of the orientation of the large-scale circulation cells eastwardly from Indian Ocean to the central Pacific. In addition, the tropical cyclone formation may be related to this oscillation [*Nakazawa*, 1986]. A possible mechanism may be the Ekman Pumping in the boundary layer, which may provide large-scale convergence for tropical cyclone occurrence [*Madden and Julian*, 1994]. Tropical influences on California precipitation are emphasized by heavy precipitation over California under the conditions that rainfall in the subtropical eastern Pacific is suppressed and convection in the central Pacific is enhanced [*Mo and Higgins*, 1998b]. On the other hand, no systematic relationship was found between annual variability in the amplitude of the MJO and the occurrence of the extreme events in California [*Jones*, 2000]. Controversially, the phase of the MJO has a substantial systematic effect on intraseasonal variability in precipitation in Oregon and Washington [*Bond and Vecchi*, 2003]. As will be shown in the next chapters, the extreme precipitation over Oregon, Washington, and California is a result of the same weather pattern. Therefore, MJO may have an effect on extreme precipitation over California.

In conclusion, the current operational methodology is a quasi-deterministic procedure as mentioned by *Dawdy and Lettenmaier* [1987]. Accordingly, our goal is to develop a deterministic procedure in this sense. Moreover, the procedure, developed here, will accommodate stochastic components at the same time, since stochastic-dynamic methods may provide better solutions than fully deterministic approaches due to the capability of stochastic-dynamic methods estimating uncertainties (initial condition, observation, imperfect parameterization, etc) quantitatively [*Joshi and Sikka*, 1986].

1.3 Research Objectives

The main objective of this dissertation is to model physically possible maximum precipitation based on 42-year historical data, assuming no climate change effect included, to

be utilized in determining the appropriate cloud microphysics, cumulus, and planetary boundary layers parameterization schemes/packages of the Weather Research and Forecast (WRF-ARW) model for the American River Watershed (ARW). "The historical record of extreme events may not be representative of future frequencies of extreme events in the case where the processes governing extreme event occurrence change. This may result from climate change if such occurs on the time scale of these observation collections" [T. R. Ginn, 2010, personal communication].

One of the aims of this dissertation is to show that the current probable maximum precipitation (PMP) estimations for AR are outdated and the current numerical weather prediction models can simulate PMP more accurately than the traditional method. Until now, PMP calculations have been performed by statistical methods in which physical phenomena were tabulated based on historical data by which those tables were updated with the occurrence of major storms. Those tables have been very useful for the time when physically based models could not be used. With the current modeling technology, although it may not be possible to obtain perfect results, it is possible to make improved estimations with certain confidence limits.

The main research needs of this study are parallel to the needs of numerical atmospheric models concerning improvements in initial and boundary conditions (IC/BC) and in model physics. The physics of the models get weaker with the simulations of finer resolutions in order to obtain more spatial detail on atmosphere. The problem becomes more complex due to finer resolutions that are required to solve more unknowns dealing with detailed physics. Local factors become more significant when the problems need to be adapted to the combination of the effects with varying scales. For instance, at the most coarse resolution R15 ($\sim 4.5^\circ \times 7.5^\circ$), Parallel Climate Model [Barnett et al, 2004] resolves only two grid points

over California. This means that if one were to model precipitation, orography cannot be considered. On the other hand, a local model can only simulate precipitation due to orography. Several techniques exist [Federico, 2006] to overcome this scale problem in order to combine the effects related to different scales, but the main deficiencies are still the IC/BC issues and model physics.

1.4 Methodology

In order to determine probable maximum precipitation, a physically based deterministic modeling approach is proposed. Considering advantages and disadvantages of several atmospheric models, The Weather Research and Forecasting Model (WRF) model has been selected for PMP modeling due to the following reasons:

1. The WRF model incorporates advanced numeric and data assimilation techniques, a multiple relocatable nesting capability, and improved physics, particularly for treatment of convection and mesoscale precipitation.
2. It is intended for a wide range of applications, from idealized research to operational forecasting, with priority emphasis on horizontal grids of 1-10 kilometers.
3. The WRF interface is intended to be user friendly to allow easy exchange of packages with other models and/or to upgrade them.

The WRF model is called one of the next generation models that some organizations combine with their own models. For instance, NCAR's Mesoscale and Microscale Meteorology Division (MMM) is going to migrate its own research to the WRF which will replace NCAR/Pennsylvania State MM5 model. NOAA's Forecast Systems Laboratory (FSL) will gradually transfer its development efforts from its RUC model to the WRF model.

NOAA's National Centers for Environmental Prediction (NCEP) will implement the WRF model as a high-resolution nest within its operational regional forecast model (Eta) and will consider it as a replacement for its regional model [Rasmussen, 1999].

Using the WRF model and based on a 42 extreme event record, the best physical options for simulating extreme conditions more accurately will be determined first for the domain of interest. After this step of calibration and validation of the model, several maximization methods will be performed in order to determine a physical range for probable maximum precipitation. An upper limit for precipitation is expected to be determined so that one can make an interpretation for an optimum PMP distribution that is sought for the AR basin, the focus of this study.

1.5 Scientific Value

The main contribution of this study is to develop a new methodology by which one can determine physically possible maximum precipitation values that will provide input to the civil engineering computations for the design and management of such structures as dams, levees, spillways and highways. Studies show that PMP values may be either too high which result in over-design, or too low resulting in excessive flood control costs depending on the location. For this reason, PMP values should be determined according to the location, and the strength of the proposed method is that the PMP can be evaluated accurately for any location even when there exist no observations.

The usage of maximum precipitation values as initial and boundary conditions in flood simulation models would be another value of this dissertation, since they can help improve the accuracy of Probable Maximum Flood (PMF) estimations.

As a secondary scope of this dissertation, further contribution may be related to the quantitative precipitation forecasting (QPF) purposes, especially for the management of dam reservoirs to provide an early warning which can help to reduce the risk of flooding with emergency levee constructions.

This work may also provide novel information on climate change related extreme events, whose importance is emphasized by IPCC as an announcement in the new special report on “Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation.” [IPCC, 2009]. Further climate change related contribution of this work may comprise coastal engineering applications that are closely related to eustatic sea level rise and precipitation whose change is projected by IPCC [2007] in terms of storm intensity and severity.

1.6 Outline

In this first chapter, the motivation for introducing the concept of probable maximum precipitation, its calculation methods in literature and its importance in civil engineering applications is defined, emphasizing that the traditional method needs to be updated. The research objectives of this dissertation, focusing on the American River Watershed, are stated, and the mechanisms, which bring extreme precipitation over this domain of interest, are investigated.

In the second chapter, the proposed method shall be introduced in more detail, and the physics behind it will be emphasized.

The third chapter examines the applicability of the developed new method. The best physics options of the model shall be determined in terms of cumulus parameterization,

microphysics, and planetary boundary layer for the domain of interest, comparing basin averaged and point observations of precipitation.

In the fourth chapter the maximization techniques of precipitation shall be elucidated, and shall be introduced as new probable maximum precipitation calculations.

In the fifth chapter the results of application of the developed methodology shall be discussed in detail, comparing the results of the traditional and other methods proposed in the literature.

In the sixth chapter the dissertation shall be concluded, stating the future goals after summarizing the application results and stating the conclusions on the proposed methodology.

CHAPTER II

Methodology

2.1 The Weather Research and Forecasting (WRF) model description

The Weather Research and Forecast Model (WRF) [*Skamarock et al.*, 2008], called the next generation numerical weather prediction system, has been developed with the partnership of NCAR, the National Oceanic and Atmospheric Administration (the National Centers for Environmental Prediction (NCEP) and the Forecast Systems Laboratory (FSL)), the Air Force Weather Agency (AFWA), the Naval Research Laboratory, Oklahoma University, and the Federal Aviation Administration (FAA). The replacement of the models of those organizations (MM5, RUC, ETA) with the WRF has been gradually started. The current WRF (Weather Research and Forecasting Model) software framework (WSF) supports two dynamical solvers: the Advanced Research WRF (WRF-ARW) that is used in this research, developed and maintained by the Mesoscale and Microscale Meteorology Division of NCAR, and the nonhydrostatic Mesoscale Model (NMM) developed by the National Centers for Environmental Prediction with user support provided by the Developmental Testbed Center (www.wrf-model.org).

The equations in this sub-section are summarized from the Advanced Research WRF Description-Version3 [*Skamarock et al.*, 2008].

The WRF is a Eulerian, nonhydrostatic, fully compressible, scalar variable conserved three-dimensional primitive equation model. The prognostic equations for each variable (wind, potential temperature, moisture and hydrometeor fields) are formulated in flux form using a terrain-following mass vertical coordinate denoted by η and defined as,

$$\eta = (p_{dh} - p_{dht}) / \mu_d \quad (2.1)$$

where mass of dry air, μ_d , is

$$\mu_d = p_{dhs} - p_{dht} \quad (2.2)$$

p_{dh} denotes the hydrostatic component of the pressure for dry atmosphere, p_{dhs} and p_{dht} refer to values along the surface and top boundaries, respectively [Laprise, 1992]. η varies from a value of 1 at the surface to 0 at the top boundary of the model domain. The flux form of moist Euler equations in mass vertical coordinate can be written as,

Conservation of momentum in x:

$$\partial_t U + [\nabla \cdot (\mathbf{V}u)] + \mu_d \alpha \partial_x p + (\alpha / \alpha_d) \partial_\eta p \partial_x \phi = F_U \quad (2.3)$$

Conservation of momentum in y:

$$\partial_t V + [\nabla \cdot (\mathbf{V}v)] + \mu_d \alpha \partial_y p + (\alpha / \alpha_d) \partial_\eta p \partial_y \phi = F_V \quad (2.4)$$

Conservation of momentum in η :

$$\partial_t W + [\nabla \cdot (\mathbf{V}w)] - g [(\alpha / \alpha_d) \partial_\eta p - \mu_d] = F_W \quad (2.5)$$

where $\nabla \cdot (\mathbf{V}u)$, $\nabla \cdot (\mathbf{V}v)$, and $\nabla \cdot (\mathbf{V}w)$ are the flux forms of mass divergence in a terrain

following coordinate for x, y, and η directions, respectively.

Conservation of energy (Thermodynamic Energy equation):

$$\partial\Theta + (\nabla \cdot \mathbf{V}\theta) = F_\theta \quad (2.6)$$

Conservation of mass (Continuity equation):

$$\partial_t \mu_d + (\nabla \cdot \mathbf{V}) = 0 \quad (2.7)$$

Change in Geopotential:

$$\partial_t \phi + \mu_d^{-1} [(\mathbf{V} \cdot \nabla \phi) - gW] = 0 \quad (2.8)$$

Conservation of Water:

$$\partial_t Q_m + (\nabla \cdot \mathbf{V} q_m) = F_{Q_m} \quad (2.9)$$

along with the diagnostic relation for the specific volume for dry air is $\alpha_d = 1/\rho_d$, and

specific volume for moist air is $\alpha = \alpha_d (1 + q_v + q_c + q_r + q_i + q_g + q_s)^{-1}$

$$Q_m = \mu_d q_m \quad (2.10)$$

$$q_m = q_v, q_c, q_r, q_i, q_g, q_s \quad (2.11)$$

where q_m is the mixing ratio (mass per mass of dry air) for water vapor, cloud water, rain,

ice, graupel, and snow, respectively.

$$\partial_{\eta}\phi = -\alpha_d\mu_d \quad (2.12)$$

and equation of state,

$$p = p_0 (R_d\theta_m / p_0\alpha_d)^{\gamma} \quad (2.13)$$

where

$$\theta_m = \theta(1 + (R_v/R_d)q_v) \approx \theta(1 + 1.61q_v) \quad (2.14)$$

The subscripts x , y , and η denote differentiation; $\gamma = c_p/c_v = 1.4$ is the ratio of the heat capacities at constant pressure and volume, for dry air. R_d is the gas constant for dry air, p_0 is a reference pressure. F_U , F_V , F_W , F_{θ} , and F_{Q_m} represent forcing terms arising from model physics, turbulent mixing, spherical projections, and the rotation of the Earth. θ is the potential temperature, and non-conserved variables are the geopotential, $\phi = gz$ and the pressure, p . Since $\mu_d(x,y)$ is the mass per unit area within the column in the model domain, flux form of the variables are,

$$\mathbf{V} = \mu_d \mathbf{v} = (U; V; W) \quad (2.15)$$

$$\Omega = \mu_d \dot{\eta} \quad (2.16)$$

$$\Theta = \mu_d \theta \quad (2.17)$$

where $\mathbf{v} = (u; v; w)$ are the covariant velocities, which are the velocities of a cartesian coordinate system transformation, while $\omega = \dot{\eta}$ is the contravariant vertical velocity, which is a vertical velocity of the inverse of that cartesian coordinate system transformation.

For temporal discretization diverse time-integration schemes are used. The WRF-ARW solver uses a third-order Runge-Kutta (RK3) time integration scheme [Wicker and Skamarock, 2002]. Forward-backward time integration scheme is used for both horizontally propagating acoustic modes and gravity waves. The integrations of buoyancy oscillations and vertically propagating acoustic modes are integrated by a vertically implicit scheme over smaller time steps to maintain numerical stability.

For spatial discretization, The WRF-ARW solver uses Arakawa-C horizontal grid staggered scheme [Arakawa and Lamb, 1977]. In the vertical direction, variables are defined with wind/mass fields on half η layers and the vertical velocity and TKE at the full layers.

The WRF has downscaling/upscaling capabilities and many modeling options for various atmospheric processes. The WRF itself includes terrain elevation, land cover and land use data sets from USGS at various resolutions that cover the whole globe. The finest resolution of these data sets is 30 seconds in both latitudinal and longitudinal directions, which corresponds to about 1 km in length in mid-latitudes.

The WRF uses ordinary Cartesian grids in the horizontal directions and a terrain-following η coordinate in the vertical direction. As a function of pressure, a dimensionless quantity eta is used to define the vertical levels between zero and one corresponding to the top and bottom of the troposphere, respectively. One may choose ten to forty vertical levels

which are not necessarily equally spaced. In the WRF, C type staggering [Arakawa and Lamb, 1977] is used for the calculation of the variables on grid cells for two horizontal dimensions that state variables/scalars (temperature, pressure and specific humidity) are computed at the middle of the grid cells shown as θ in Figure 2.1 while the horizontal velocity components are simulated at the half distance of the nodes of these grid cells. The advantage of C type staggering is that convergence and pressure terms are simulated in one unit distance only, which doubles the resolution of A type staggering. Thus geostrophic adjustment is calculated with improved accuracy. On the other hand, C staggering might be disadvantageous for inertia-gravity wave simulations [Kalnay, 2003]. In vertical, state variables are defined at the middle of the each eta level, while vertical velocity is computed at the eta levels.

The WRF model is globally re-locatable with three map projections: Polar stereographic, Lambert conformal and Mercator. The map projections support different true latitudes for Lambert conformal projection, which we use for our domain of interest.

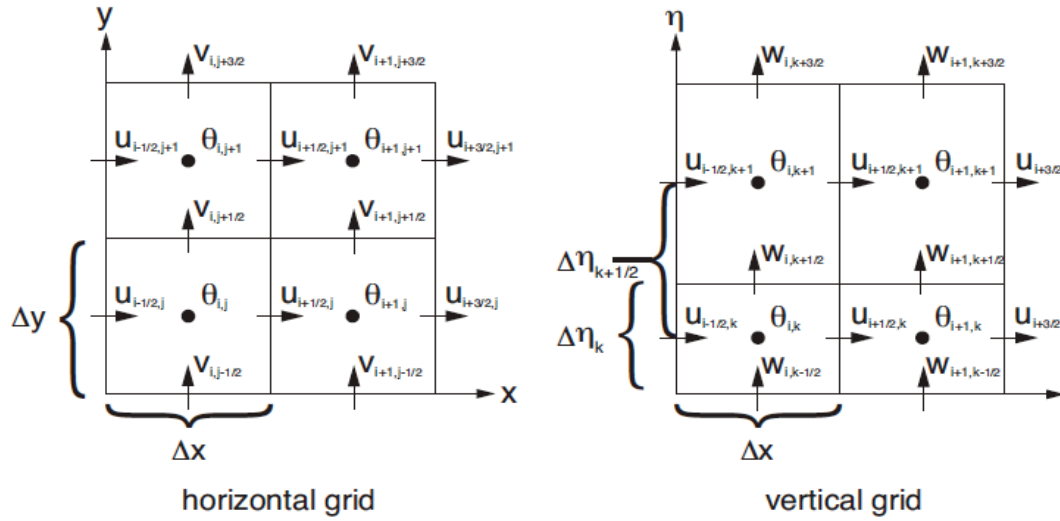


Figure 2.1 Horizontal and vertical grids of the WRF (ARW-Version3)

The model grid sizes are flexible and it has multiple nesting capabilities so that multiple domains (three nested domains are used in this study) could be run in the WRF, simultaneously. Each domain takes information from its parent domain at every time-step, and runs three time steps for each parent step before feeding back information to the parent domain on the coincident interior points. The feedback distinguishes two-way nesting from one-way nesting, and allows the nests to affect the coarse mesh solution, leading to better behavior at outflow boundaries. However there is significant overhead cost associated with the boundary interpolation and feedback at every time step.

Due to the fact that the sub-grid scale processes are not simulated explicitly, they need to be somehow adjusted so that their significant influence on larger scales can be represented accurately. These adjustments are called parameterizations that are mainly applied to boundary layer, cloud, hydrological, radiation/chemical and ocean/land processes, in regional mesoscale models [Arakawa, 1997]. Reynolds averaging method is applied to handle both low and high-resolution effects where resolved processes are determined by grid-box averages whereas perturbations need to be parameterized. It is important to note at this point that it is also possible to solve those five main processes explicitly, including the necessary closure assumptions. They may even provide better representations than parameterization techniques, but the results of such an approach still do not compensate the cost and efficiency, although computers are getting extremely powerful.

The WRF model has a wide range of physical process routines such as those handling advection, diffusion, radiation, planetary boundary layer, land surface, cumulus parameterization and cloud microphysics. In this research, we only focus on the options of cumulus parameterization, cloud microphysics and boundary layer physics for precipitation sensitivity analysis purposes.

2.2 Cloud Microphysics Schemes

The parameterization of hydrological and chemical processes depends on the definition of source-sink terms in their prognostic equations. Regarding hydrological processes, three prognostic equations, called conservation of water equations, are added to the governing equations with three additional unknowns in specific humidity values for different phases of water. Freezing, deposition, condensation, and conversions of the phase changes are parameterized as source-sink terms for the closures.

Cloud microphysics parameterization is handled by either using bin or bulk microphysics schemes in numerical weather prediction models. Bin (spectral) microphysics schemes that simulate the size spectra of liquid and ice particles are computationally more expensive than the bulk schemes, which have very simplified parameterizations especially when one moment of the particle size distribution is predicted [*Lynn and Khain, 2007*]. All microphysics parameterization options of the WRF are bulk schemes that are called two-moment schemes if they predict both mass and number densities. Cloud microphysics schemes resolve precipitation processes depending upon grid-scale saturation. Assuming that grid boxes are uniform, these processes are activated whenever the saturation is reached. Ice phase inclusion regarding graupel or hail depends on microphysics scheme. Temperature tendencies, all moist variables, and non-convective surface rainfalls are the outputs of those microphysical processes. They also provide cloud information to radiation schemes. All nine microphysics options of the WRF, shown in Table 2.1, are evaluated in this study for sensitivity analysis purposes.

Table 2.1 The WRF microphysics options (ARW-Version3)			
Scheme	Number of Variables	Ice-Phase Processes	Mixed Phase Processes
Kessler	3	No	No
Purdue Lin	6	Yes	Yes
WSM3	3	Yes	No
WSM5	5	Yes	No
WSM6	6	Yes	Yes
Eta GCP	2	Yes	Yes
Thompson	7	Yes	Yes
Goddard	6	Yes	Yes
Morrison 2-Moment	10	Yes	Yes

2.2.1 Kessler scheme

Kessler scheme, adapted from COMMAS [*Wicker and Wilhelmson, 1995*] model, is a simple warm cloud scheme where cloud water and rain fields are predicted explicitly with microphysical processes without any ice phase processes. These microphysical processes are the production, fall, and evaporation of rain; the accretion and auto-conversion of cloud water; and the production of cloud water from condensation [*Kessler, 1969* (K69, hereafter)].

2.2.2 Purdue Lin scheme

Six classes of hydrometeors are included: water vapor, cloud water, rain, cloud ice, snow, and graupel. Production terms simulated for snow are ice crystal aggregation, accretion of cloud ice by snow, accretion of cloud water by snow, accretion of cloud ice by rain, accretion of rain by cloud ice particles, accretion of rain for snow, accretion of snow for rain, accretion of snow by hail/graupel, depositional growth of snow, melting of snow to form rain, cloud water transformation to snow by deposition, cloud ice transformation to snow by riming. Production terms calculated for hail/graupel are aggregation of cloud ice to form snow, accretion of cloud water by hail, accretion of cloud ice by hail, accretion of rain by hail, wet growth of hail, raindrop freezing, sublimation of hail, melting of hail. Production terms for rain are, auto-conversion of cloud droplets, accretion of cloud water by rain,

freezing of raindrops, melting of raindrops, evaporation of rain [Lin *et al.*, 1983; Rutledge and Hobbs, 1984 (RH84)] Heat exchange and phase change of water substance are iteratively balanced in saturation adjustment part of the scheme with the inclusion of ice phase change [Tao *et al.*, 1989].

2.2.3 The WRF Single-Moment 3-class (WSM3) scheme

WSM3 is a simple-ice scheme, adopted from Dudhia, 1989 [D89] which is also a continuation of Hsie scheme and Rutledge and Hobbs ([1983], (RH83)), that predicts vapor, cloud water or ice, and rain or snow, using three arrays. Cloud water and rain processes are taken into account when temperatures are above the temperature of freezing, while temperatures are either equal to or below the freezing temperature when the same arrays are treated for cloud ice and snow calculations. Cloud ice number concentrations are diagnosed from their mixing ratio. Intercept parameter for snow is temperature dependent, ice number concentrations are cloud-ice-mass dependent, and ice processes and auto-conversion of cloud water to rain are slightly different from D89 and RH83. Sedimentation of ice crystal is added to the scheme [Hong *et al.*, 2004]. This scheme does not take into account super-cooled water processes and gradual melting rates of snow. Therefore, it is not a mixed phase scheme.

2.2.4 The WRF Single-Moment 5-class (WSM5) scheme

WSM5 differs from WSM3 in that five hydrometeors (water vapor, rain, snow, cloud ice, and cloud water) are computed in their own arrays [Hong *et al.*, 2004; Hong and Lim, 2006]. WSM5 is a mixed phase scheme where supercooled water processes and gradual melting rates of snow are simulated.

2.2.5 The WRF Single-Moment 6-class (WSM6) scheme

The six-class scheme is similar to WSM5 scheme except that graupel is included as the sixth hydrometeor. Regarding to graupel-related terms, it is similar to Purdue-Lin scheme and RH84, although its ice-phase behavior is similar to WSM family schemes [Hong *et al.*, 2004]. Terminal velocity, in other words fall speed of snow and graupel, is unified by its mass weighted average. Accretion rates of ice, cloud water and rain are modified according to their new terminal velocities with the elimination of snow-graupel accretion [Dudhia *et al.*, 2008]. For a low-resolution grid (i.e, greater than 10km), WSM family schemes simulate precipitation similarly, although WSM6 simulates precipitation better for high-resolution grids (i.e., less than 10km) [Hong and Lim, 2006].

2.2.6 Eta Grid-scale Cloud and Precipitation (2001) scheme- EGCP01

EGCP01, known also as Eta Ferrier, is a mixed-phase and six-class scheme. It assumes that the size distribution of precipitating ice is a function of temperature [Ryan, 1996]. Lookup tables are used for rain, precipitating ice and fall speed of rimed ice, which is a function of rime density. The gradual sedimentation of ice particles from upper levels is taken into account. Total condensation of cloud water, rain, and ice and their fractions are predicted in this scheme. Ice is categorized as small ice crystals, snow, graupel, and sleet.

2.2.7 Thompson et al. scheme

Thompson scheme, which is also a bulk parameterization, can be classified as the most sophisticated one among the WRF microphysics. It is an upgrade version of Reisner *et al.* [1998] and Thompson *et al.* [2004]. The last Thompson scheme (The WRF-ARW V3.1.1) has also new modifications such as two-moment implication that is not mentioned in Thompson *et al.* [2008] [G. Thompson, 2009, personal communication]. The sum of exponential and

gamma distributions is used to describe snow size distribution which depends on both ice water content and temperature. Unlike any other microphysics schemes, snow is assumed to be non-spherical and its density varies inversely with diameter that is very close to observations. A threshold size of ice crystals are arbitrarily determined for the process of depositional growth onto cloud ice particles, so that slowly falling tiny ice crystals coexist with more rapidly falling snow. Regarding riming process, this scheme uses a variable collection efficiency based on volume diameter of snow and cloud water [*Wang and Ji*, 2000], rather than a constant used by other schemes. Constants that are used to calculate terminal velocities of snow, are matched to vertically pointing Doppler radar data.

2.2.8 Goddard Cumulus Ensemble Model (GCE) scheme

The GCE [*Tao and Simpson*, 1993] is a one-moment bulk microphysical scheme where cloud water and rain are parameterized by K69 and the parameterization of cloud ice, snow, and hail/graupel is mainly based on *Lin et al.* [1983] with additional processes from RH84. The third class of ice can be chosen either as graupel or hail, whereas only two classes of ice can be simulated with the options of ice and graupel or ice and snow [*McCumber et al.*, 1991]. A new saturation technique, designed to ensure that super saturation (sub-saturation) cannot exist at a grid point that is clear (cloudy), was added [*Tao et. al.*, 1993; *Tao et al.*, 2003]. There is also a control subroutine for conservation of water budget.

2.2.9 Morrison Scheme

The Morrison scheme is a two-moment bulk microphysics scheme that is based on *Morrison et al.* [2005] and *Morrison and Pinto* [2006]. In this scheme, mass mixing ratios and number concentrations of five hydrometeor species; cloud droplets, cloud ice, snow, rain, and graupel, are predicted. The cloud and precipitation particle size distributions are

represented by gamma functions. Intercept and slope parameters of this distribution are derived from the predicted number concentrations, mixing ratio, and shape parameter for each species. All particles are assumed to be spheres and bulk particle densities of *Reisner et al.* [1998] are used. For the precipitation species shape parameter is selected as 0, so that size distributions of these species are exponential functions similar to Marshall-Pallmer distributions [*Morrison et al.*, 2009].

2.3 Cumulus Parameterization

The parameterization of the cloud process, the so-called cumulus parameterization, is seen as one of the most complex problems in numerical weather prediction models. The main goal of cumulus parameterization is to represent the collective effect of the sub-grid scale clouds, which cannot be resolved explicitly. Cumulus parameterization schemes are based on the determination of the effects of cumulus convection in sub-grid scale regarding condensation in the updraft, evaporation in the downdraft, cooling due to the evaporation of falling rain below the cloud base, turbulent mixing at the cloud edge with the environment, entrainment, detrainment, and subsidence compensation in the boundary layer. They resolve sub-grid scale vertical fluxes and rainfall due to convective clouds. They produce columnar moisture, temperature tendencies and surface convective rainfall. Some cumulus parameterization schemes also produce columnar cloud tendencies. If the grid is fine enough (i.e., less than 5 km) to resolve updrafts and downdrafts then there is no need to use cumulus scheme.

Convective adjustment technique is another way to resolve the vertical structure of the atmospheric column without simulating the explicit convective processes [*Frank and Molinari*, 1993]. In this technique, temperature and moisture is first predicted for a time step at each model grid neglecting condensation and development of any unstable lapse rates. Then the

vertical profiles of temperature and moisture at each grid point are examined for super adiabatic lapse rates and/or super saturation. In the unsaturated case, if the lapse rate exceeds the dry adiabatic value, it is restored to this value. If the air is saturated, and the calculated lapse rate exceeds the moist adiabatic lapse rate, then any excess moisture in the model grid must be condensed isobarically with the latent heat warming the air. Therefore, the temperature and the specific humidity are adjusted to bring the air in the model grid to a saturated state. This way, the model can compute precipitation through the computation of condensation at each model grid.

Table 2.2 The WRF cumulus parameterization options (ARW-Version3)			
Scheme	Cloud Detrainment	Type	Closure
Kain-Fritsch	Yes	Mass Flux	CAPE Removal
Betts-Miller-Janjic	No	Adjustment	Sounding Adjustment
Grell-Devenyi	Yes	Mass Flux	Various
Grell-3D	Yes	Mass Flux	Various

2.3.1 Kain-Fritsch scheme

Kain-Fritsch, a complex cloud-mixing scheme [Kain, 2004], is the modification of Fritsch-Chappell type schemes [Kain and Fritsch, 1990; Kain and Fritsch, 1993]. It determines updraft and downdraft properties with releasing convective available potential energy (CAPE), the maximum work done by buoyancy, given time scale. It is a mass flux type scheme and it can detrain cloud and precipitation in addition to vapor. The minimum entrainment rate is defined as 50% of the maximum possible entrainment rate to suppress convective initiation for unstable and dry environments. Maximum possible entrainment rate is controlled by cloud radius. Therefore, this radius is modified to alter as a function of sub-layer convergence [Frank and Cohen, 1987]. Deep convection activation is suppressed in weakly convergent or divergent environments, while it is enhanced in strongly convergent regimes.

The other necessary term for deep convection activation, minimum cloud depth, is a function of cloud-base temperature in this scheme rather than a constant as in its other versions. This modification helps to improve deep convection activation in shallow clouds, especially when ice-phase processes are active. In the conditions when minimum cloud depth cannot be adequate for deep convection, the scheme allows the formation of the non-precipitating clouds. CAPE removal is used for the closure assumption where CAPE is based on the path of an ascending parcel with dilution.

2.3.2 Betts-Miller-Janjic scheme

The Betts-Miller-Janjic (BMJ) scheme [Janjic, 1994; Janjic, 2000] is a modified version of the Betts-Miller (BM) convective adjustment scheme [Betts, 1986; Betts and Miller, 1986]. The major modification is related to the characterization of the deep convection regimes where the parameters used in moisture profile and relaxation time are switched to variables that are dependent upon a new parameter called cloud efficiency which is a function of mean cloud temperature, precipitation, and entropy change [Janjic, 1994]. For shallow convection moisture profile, a constraint is added to ensure that entropy change needs to be small and nonnegative. In this scheme there are two layers over the oceans. One is a viscous layer where the molecular diffusion is the driving mechanism for the vertical transport. The other is a layer above the viscous layer where turbulence is responsible for the vertical transport.

2.3.3 Grell-Devenyi ensemble scheme

Grell-Devenyi scheme is based on a convective parameterization scheme developed by Grell [1993]. In Grell scheme clouds are pictured as two steady-state circulations, caused by an updraft and a downdraft. There is no direct mixing between cloud air and environmental air, except at the top and the bottom of the circulations. Cloud mass flux is constant with

height, and there is no entrainment or detrainment along the cloud edges. Therefore, the updraft and downdraft mass fluxes at their originating levels represent the mass fluxes through all the layers of a cloud. The main state variable of this scheme is the upward mass flux at the cloud base. It is determined from the buoyant energy, which is a function of the change in buoyant energy due to convection and the change in buoyant energy due to large-scale destabilization. Finally, the rainfall is computed from a relation of water condensation in updraft, upward mass flux at the cloud base and precipitation efficiency [*Fritsch and Chappell*, 1980]. On the other hand, Grell-Devenyi scheme introduces a new convective parameterization framework where a large ensemble of assumptions used in Grell scheme is computed and the optimal value is given to the three-dimensional model as a weighted average. Parameterization ensembles that have at least 144 members are classified as dynamic control, feedback, and static control. Dynamic control shows the modulation of the convection by the environment, called feedback, and static control is the cloud model that is used to determine cloud properties [*Grell and Devenyi*, 2002].

2.3.4 Grell-3D ensemble scheme

This scheme is based on the ensemble mean convective parameterization approach as introduced in Grell and Devenyi scheme. In Grell-3D, quasi-equilibrium approach is not applied to the ensemble members. Subsidence effects are extended to the neighboring columns so that the scheme is more accurate for grid sizes less than 10km.

2.4 Planetary Boundary Layer (PBL) Parameterization

There are a number of formulations for turbulent mixing and filtering available in the WRF solver. Some of them are used for numerical reasons, and other filters are designed to represent physical sub-grid turbulence processes. The ARW solver allows sub-grid scale

turbulence to be parameterized as it is treated in cloud-scale models including horizontal mixing. However, when a PBL scheme is used, all other cloud-scale vertical mixing is disabled, and vertical mixing is parameterized in the chosen PBL scheme. [Skamarock *et al.*, 2008; Laprise, 1992]. Planetary Boundary Layer schemes represent sub-grid vertical fluxes due to turbulence, and they are mostly distinguished by the treatment of the unstable boundary layer, providing columnar tendencies of heat, momentum and moisture. PBL schemes may also provide cloud tendencies and frictional effects on momentum. They are subdivided as surface layer, boundary layer and free atmosphere, and they have interaction with fluxes from surface layer and land-surface schemes. These one-dimensional schemes assume a clear separation between sub-grid and resolved eddies.

The modeling of vertical fluxes of momentum, heat and moisture in the atmospheric boundary layer are computed by means of the standard turbulent transport schemes with the drag coefficient as a function of the stability conditions. Deardorff [1972] suggested solving the planetary boundary layer parameterization problem in four steps. In the first step, the vertically averaged mean values of wind velocity, potential temperature, and specific humidity are determined by the extrapolation technique using initial boundary layer height. In the second step, using the mean and surface values of state variables, Bulk Richardson Number is calculated in order to estimate the surface flux of momentum, heat, and moisture. The equations are treated differently above and inside the surface layer, which requires that the vertical flux of a variable at surface is less than that of 0.025 times of boundary layer, the so-called anemometer level. In the surface layer, dimensionless vertical gradients of wind, temperature, and specific humidity are functions of height and Monin-Obukhov length which, in turn, is dependent on friction velocity; and the surface value and kinematic vertical flux of virtual potential temperature, gravitational acceleration, and von

Karman constant. Virtual potential temperature and its kinematic vertical flux determine the thermal stability of PBL whose theory is used at the third step, in order to calculate the direction of surface level velocity, which is determined by means of horizontal pressure gradient at the surface. In the forth step, the atmospheric boundary layer height is simulated for one time step ahead using prognostic equations and simpler relationships for unstable and stable cases, respectively. The prognostic equation of boundary layer height is a function of vertical velocity at that level, advection of boundary layer height, penetrative convection related source term, and lateral diffusion of its height, which is related to an eddy coefficient.

Surface and boundary layer parameterizations are based on averaged sub-grid scale fluxes for which three different closure techniques exist: 1. Zeroth order closure assumes that grid-scale field is well mixed in order to neglect the vertical turbulent flux, 2. First order closure is also known as K-theory where the vertical flux is parameterized as if it is only a diffusion process. The determination of the diffusion (exchange) coefficient, also known as eddy diffusivity, is a complex problem, 3. Second order closure technique is based on solving the vertical flux as a prognostic equation in which triple products of turbulent terms are parameterized by K-theory [Stull, 1988]. In a regional mesoscale model, PBL parameterization is based on the quasi-stationary assumption that large-scale forcing gets very rapid feedback from PBL whose vertical structure is represented by the small-scale turbulent fluxes [Haltiner and Williams, 1980], and by either a single layer or a number of discrete levels which can be subdivided into a viscous sublayer, a surface layer, and a transition layer [Pielke, 2002].

Main features of PBL parameterization options of the WRF are introduced summarized in Table 2.3.

Table 2.3 The WRF planetary boundary layer parameterization options (ARW-Version3)			
Scheme	Unstable PBL Mixing	Entrainment Treatment	PBL Top
MRF	K Profile and countergradient term	Part of PBL mixing	Critical bulk Ri
YSU	K Profile and countergradient term	Explicit term	Buoyancy profile
MYJ	K from diagnostic TKE	Part of PBL mixing	TKE
ACM2	Transilient mixing up, local K down	Part of PBL mixing	Critical bulk Ri

2.4.1 Medium Range Forecast Model (MRF) PBL

Diffusion in the mixed boundary layer is represented by a nonlocal diffusion approach [Troen and Mahrt, 1986]. In the free atmosphere, diffusion is treated by local diffusion approach in which the diffusivity coefficients are parameterized as functions of the local Richardson number. The PBL height is a function of critical bulk Richardson number, horizontal wind speed and virtual potential temperature [Hong and Pan, 1996].

2.4.2 Yonsei University (YSU) PBL

The Yonsei University (YSU) PBL parameterization scheme is a modified version of the MRF PBL scheme regarding entrainment processes at the top of the PBL where an asymptotic entrainment flux term is added to the turbulence diffusion equations at the inversion layer. Moreover, a new boundary layer mixing treatment is included where mixing is increased in the thermally induced free convection regime whereas it is decreased in the mechanically induced forced convection regime [Hong *et. al*, 2006]. Two problems related to the MRF scheme, the overly rapid growth of planetary boundary layer and excessive mixing in the mixed-layer due to high wind speeds, are resolved in YSU. In this scheme the convective inhibition predictions were also improved. The stable boundary layer related tendency of the YSU scheme, where mixing is too little over the cold oceans and in continental valleys was also resolved [Hong and Kim, 2007].

2.4.3 Mellor-Yamada-Janjic (MYJ) PBL

Mellor-Yamada-Janjic (MYJ) PBL scheme is an implementation of the Mellor-Yamada Level 2.5 turbulence closure model [Mellor and Yamada, 1982] above the surface layer. For the surface layer this scheme uses the Mellor-Yamada Level 2 turbulence closure scheme that is derived from the Level 2.5 model, which assumes that the production and the dissipation terms of the turbulent kinetic energy (TKE) equation are balanced. The large-scale variables are simulated in the middle of the model layers whereas turbulence parameters are computed at the interfaces of these layers. The TKE production-dissipation equation is solved iteratively. The TKE and the master length scale are set to their lower bounds when the TKE production term is not balanced by the dissipation term, which also occurs at the level where the PBL height is determined [Janjic, 2002].

2.4.4 Asymmetrical Convective Model Version 2 (Pleim) PBL-(ACM2)

The ACM2 comes from Blackadar convective model [Blackadar, 1978] family following ACM1. In Blackadar scheme convective transport is originated from the lowest model layer, which is the surface layer, and it rises directly to all other layers within the convective boundary layer (CBL) with symmetrical return flow from each layer back to the lowest layer. In ACM1 this symmetrical return flow is turned to asymmetrical downward flows. In convectively buoyant plumes, mass fluxes are characterized by rapid upward transport. Meanwhile, in compensatory subsidence sector they are represented by gradual downward transport. In ACM2 an eddy diffusion component is added to the nonlocal transport for a better representation for the shape of the vertical profiles especially in the gradually decreasing gradient near the surface [Pleim, 2007].

2.5 Radiation Schemes

Radiation parameterization is based on the determination of the averaged vertical gradient of absorbed irradiance, which is the radiative energy per area per time, neglecting the horizontal divergence and its effect on pressure change. Longwave radiation absorption by ozone, and longwave scattering by air molecules can also be neglected. Water vapor and carbon dioxide are generally used as the primary absorbers of longwave radiation.

Radiation schemes represent radiative effects both in the atmosphere and at the surface in terms of scattering, reflection, absorption and emission of short and long wave radiation. They provide long and short wave fluxes for surface schemes. They give information about the column temperature tendencies due to vertical radiative flux divergence, and they can interact with model clouds and relative humidity. The radiative effects of diurnal cycle are treated in terms of surface sensible and latent heat flux exchanges. Heat storage capabilities over land and sea/ice surface are also integrated to diurnal cycle effects. At the top of the atmosphere insolation is computed as a function of solar constant, eccentricity factor, and solar zenith angle, which is dependent upon calendar day of the year, latitude, solar declination, and local time, as a function of the day of the year and longitude. δ -Eddington approach is used by some to simulate shortwave radiation fluxes with the multiple effects of scattering. In this approach the atmosphere is separated into vertically discrete, horizontally homogenous layers in order to solve the reflectivity and transmissivity in terms of downward and upward fluxes at the intersections of layers. This calculation is repeated for the whole spectrum, which is divided into 18 discrete intervals for ozone, oxygen, water vapor and carbon dioxide. Molecular and cloud water droplet scattering and absorption processes are also taken into account with this approximation. Longwave radiation fluxes are treated as absorption and emission processes by means of ozone, carbon dioxide and water

vapor, whose equations are basically function of Stefan Boltzman Law and Planck function. Cloud emissivity is calculated by defining effective cloud amount, which is a function of broad band emissivity and cloud liquid water path that is the columnar integral of cloud liquid water density. Meanwhile, clear sky emissivity is calculated from fractional cloud cover, which is obtained by a cloud microphysics scheme [*Hack et al.*, 1993].

For this study, the Rapid Radiative Transfer Model (RRTM) and Dudhia scheme are selected for longwave and shortwave radiation parameterization, respectively. RRTM scheme incorporates the effects of the detailed absorption spectrum considering water vapor, carbon dioxide and ozone. It is combined with the cloud-radiation shortwave scheme and interacts with the model cloud and precipitation fields [*Mlawer et al.*, 1997]. Dudhia scheme is sophisticated enough to account for longwave and shortwave interactions with explicit cloud and clear-air. It also provides surface long and short wave fluxes without calling surface radiation fluxes.

2.6 Land Surface Schemes

The hydrologic and atmospheric processes that take place at the interface between the earth surface and the atmosphere, such as infiltration and evaporation processes, are here called land surface processes. These land surface processes have scales much smaller than the horizontal resolution of mesoscale atmospheric models. The schemes that simulate the areal-average behavior of land surface processes over a computational grid of the mesoscale atmospheric model are called land surface parameterization schemes. They mainly provide ground temperature as an output, which is calculated by sensible heat, latent heat and radiative fluxes as well as surface layer atmospheric properties. Surface moisture availability, sub-soil temperature and moisture profiles can also be provided.

In this study, a thermal diffusion scheme that is adapted from a five-layer soil temperature model, which is an improved version of the force-restore method of *Blackadar* [1976] and *Deardorff* [1978], was used. Soil temperature is predicted in five layers with the thicknesses from top to the bottom of 1, 2, 4, 8, and 16 cm. Below the bottom layer, the substrate temperature is kept constant at a depth of 32 cm. Snow cover and soil moisture are fixed in time depending upon the season and landuse. In the soil heat flux equation, the soil thermal diffusivity is fixed at $5 \times 10^{-7} \text{ m}^2 \text{ s}^{-1}$ which is assumed to be an intermediate value between sand and clay soils [Dudhia, 1996]. Change in soil temperature is determined using the relation between heat flux convergence and heating:

$$\frac{\partial T_s}{\partial t} = -\frac{1}{\rho_s c_s} \frac{\partial F}{\partial z} \quad (2.18)$$

where ρ_s is soil density $[\text{kg m}^{-3}]$, c_s is specific heat capacity of soil $[\text{J kg}^{-1} \text{ K}^{-1}]$, and subscript s denotes properties of soil. Heat flux $F [\text{W m}^{-2}]$ is obtained from one dimensional simple diffusion equation:

$$F(z) = -K \rho_s c_s \frac{\partial T_s}{\partial z} \quad (2.18)$$

where $K [\text{m}^2 \text{ s}^{-1}]$ is thermal diffusivity of soil. Temperature profile of soil is initialized using the observations of ground and substrate temperature [Dudhia, 1996].

Dudhia [1996] addressed that surface air temperature of the model may not be consistent with surface observations in terms of both amplitude and phase lag depending on the initialization time of the model. He argues that this might be related to high moisture availability since soil moisture budget is not included in this package. The development of the atmospheric boundary layer is closely related to the soil moisture distribution [Maxwell et al. 2007]. Moreover, Maxwell et al. [2007] shows that a groundwater-land surface-atmosphere coupled model provides more realistic topographically-driven soil moisture distribution than an atmospheric model does alone.

More detailed information regarding the WRF model and its physics options can be obtained from *Skamarock et al.* [2008].

2.7 Model Configuration

In this research, for sensitivity and precipitation maximization analyses, the versions 3.1 and 3.1.1 of the WRF-ARW are used for a two-way nested domain configuration [*Skamarock et al.*, 2008], that features a 27 km outer fixed domain (D1) with two fixed nest domains of 9 km (D2) and 3 km (D3) grid spacing, as shown in Figure 2.2.

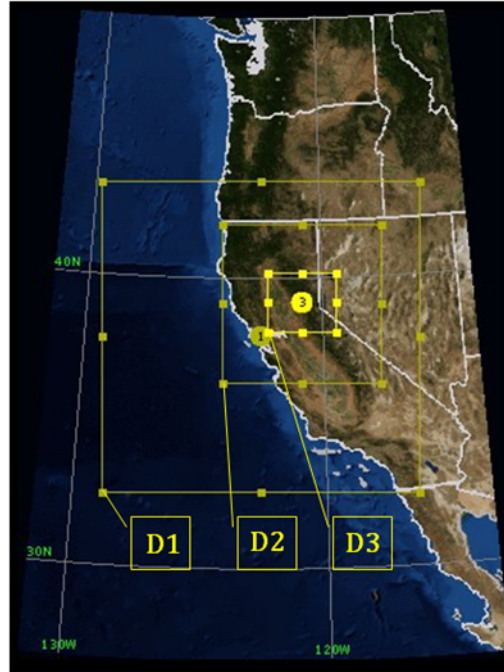


Figure 2.2 The WRF-ARW model domain configuration

The American River Watershed is centered in the finest resolution (3 km) domain. D1 consists of 43 x 44 x 28 grids. D2 has 64 x 67 x 28 grids, and D3 has 82 x 76 x 28 grid points for meridional, zonal, and vertical directions, respectively. Lambert conformal map projection is used. Cumulus parameterization schemes are only used for 27 and 9 km domains, while cloud microphysics schemes are switched on only for 9 and 3 km domains, as suggested by the WRF team. In the next chapter, all cumulus parameterization, cloud microphysics, and planetary boundary layer options of the WRF will be tested to determine the optimum physics options for the American River Watershed domain. Simulations are initialized using NCEP/NCAR Global Reanalysis Model, with a resolution of T62 (209 km) data. The simulation times are determined depending upon the period of the actual 42 storms. They are configured to start 24 hr prior to the beginning of the storm, and to stop 24 hr after the end of the storm.

CHAPTER III

Calibration and Validation of the WRF model with historical events

3.1 Introduction

In this chapter, the goal is to introduce the calibration and validation (CV) results of the WRF model in terms of precipitation, assuming that CV also comprises the other variables. Pineapple express (PE) phenomenon and PE related historical extreme precipitation events which cause floods in northern California, are introduced first. Model and observation data used for CV are presented next. Then, the CV is performed to show that the numerical weather simulation models can be used in probable maximum precipitation (PMP) estimations. Finally, the sensitivity analyses are presented regarding both precipitation amount and timing.

3.2 Historical Events

Determination of extreme precipitation is a highly complex problem due to the chaotic behavior of the atmosphere. It is especially difficult to determine extreme precipitation for design purposes that require long-term evaluations of the atmosphere in order to estimate the highest precipitation values precisely. Thus, a solid method, which can handle atmospheric dynamics in all spatial scales for long periods of time (i.e., greater than climate scales, perhaps), including the past and current events, is needed.

One of the most significant indicators of the limitation of the traditional method is the need for an update of the PMP estimate whenever a new major storm occurs. This need for an update on PMP estimate is a prospective outcome, since the traditional PMP method is not fully physically based and is only based on historical events. On the other hand, it is

important to note that the adaptation of a new method that is based on the physics only, may also not be able to solve the problem, since information is needed from the past in order to make a more comprehensive evaluation for the present and future. This may be the reason for unsatisfactory results obtained from other numerical weather prediction modeling applications on PMP [*Chen, 2005; Abbs, 1999; Cotton et al., 2002; Zhao et al., 1997*]. These studies, which suggested that the numerical weather prediction model can be used as a new tool for determining PMP in a limited way, do not take into account historical events in their simulations. Based upon the author's knowledge, the method that is proposed in this study can be considered as a first attempt in this respect, since the number of other cases, considered in their studies, are not sufficient to make a statistical inference. By taking a large sample of historical extreme precipitation events it is possible to reduce the high uncertainty due to the nonlinearity of the system. It is important to note that the numerical modeling approach would not be beneficial in PMP studies unless the method is combined with the analyses of a significant number of historical events. Currently, this point of view is also gaining more credibility in numerical weather prediction models for the purpose of ensemble forecasting. Ensemble forecasting is based fundamentally on perturbations in initial conditions to obtain more accurate predictions. Being a shortcut to ensemble forecasting, stochastic-dynamic forecasting method has been proposed but it could not be adopted due to its unfeasibility in the framework of the conventional technology [*Kalnay, 2003*].

Due to the fact that no stochastic-dynamic modeling is currently available for operational atmospheric modeling purposes, we propose a new shortcut method to stochastic-dynamic modeling without which it is not possible to make progress in the prediction of extreme events. In this research, all available historical cases shall be modeled deterministically. Then,

the results shall be evaluated statistically, assuming that the considered sample of historical events is large enough to make sound statistical inferences. Accordingly, it is necessary first to consider a large number of historical events in order to have a sufficiently large sample to make robust statistical inferences. USACE has already conducted PMP studies for the American River Basin, and have provided 52 years of 72-hour watershed average precipitation data series (Table 3.2- First 7 columns) with 42 extreme precipitation events [USACE, 2005]. It is also checked that the dates of USGS extreme flood records are consistent with the dates of USACE extreme precipitation data.

3.2.1 Pineapple Express

New Year's Eve Flood of California (December 26, 1996–January 3, 1997) has been selected as the main case study from the 42 historical extreme precipitation events in this research, since this recent flood event has abundant available data. It is also a significant example of the pineapple express phenomenon which is a weather pattern of extratropical cyclonic activity where moisture penetrates to the West coast of the US extensively (Figure 3.1), starting from Hawaiian Islands where western tropical pacific moisture and subtropical moisture merges. 1997's New Year system was one of the most severe events that have occurred in the last decade of the 20th century. In the American River Basin, the 9-day period (December 26, 1996–January 3, 1997) of precipitation was 36.34 inches in Blue Canyon, 9.57 inches in Auburn Dam Ridge, and 3.71 inches in Sacramento [NOAA, 1997].

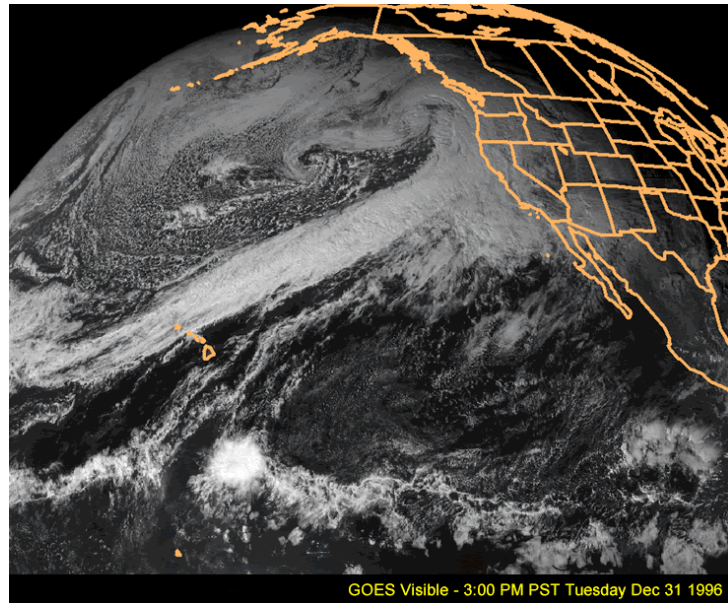


Figure 3.1 GOES Visible - 3:00 PM PST Tuesday Dec 31 1996- [http://\(www.cnrfc.noaa.gov/images/storm_summaries/jan1997/satellite/misc/visible_96dec31.gif\)](http://www.cnrfc.noaa.gov/images/storm_summaries/jan1997/satellite/misc/visible_96dec31.gif)

First, on December 21 and 22, 1996, a polar air mass-related cool winter storm started inducing rain in the valley and snow in the northern Sierra Nevada. On December 24, 1996, a warmer and wetter tropical storm connected with pineapple express became dominant, and lasted until January 3, 1997, causing snow pack melting and widespread flooding. As shown in Figure 3.2, the upper level ridge axis, aligned along the west coast of North America, began to retrograde as cooler air dropped southwest across British Columbia. An upper level high drifted over southwest Alaska as a deep upper level low undercut the upper level ridge and situated itself near 40° North and 160° West. The upper jet stream across the Pacific during the late December and early January timeframe is typically strongest from just off the Asian continent eastward to the International Dateline, between 30° and 35° North as shown in Figure 3.3. However during the December 26, 1996 through January 3, 1997 period, the upper jet stream extended across the eastern Pacific and arched from just north of the Hawaiian Islands toward the Pacific Northwest and northern California as shown in Figure 3.4. Wind speeds within this jet stream peaked near 180 knots over the western

Pacific, well above normal [NOAA, 1997].

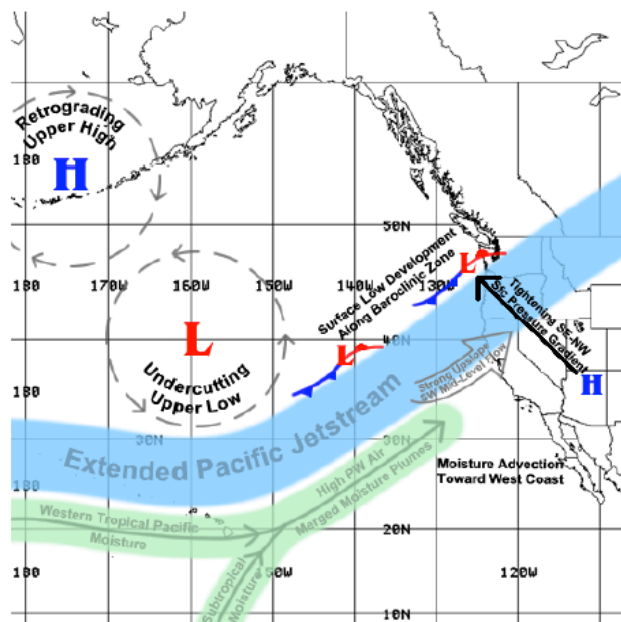


Figure 3.2 The synoptic pattern of the 1997 event [NOAA, 1997]

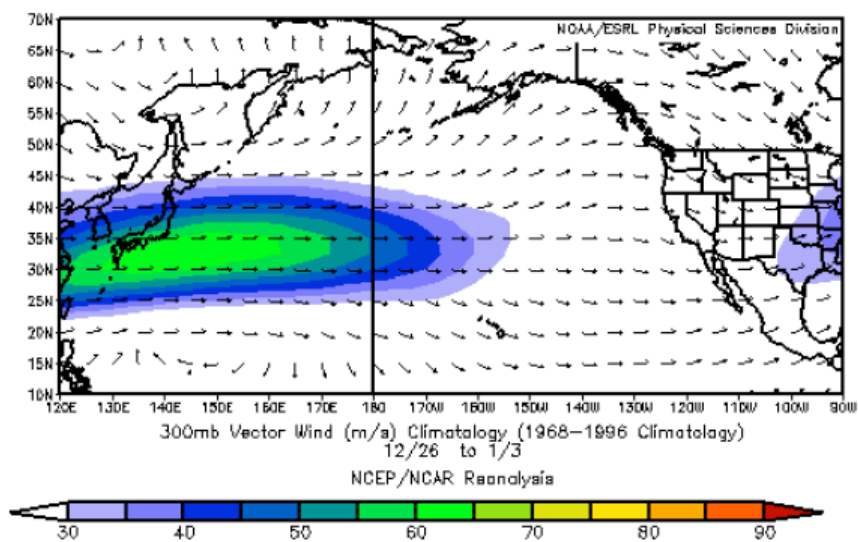


Figure 3.3 300 mb wind vector climatology for December 26 - January 3 (1968-1996) [NOAA, 1997]

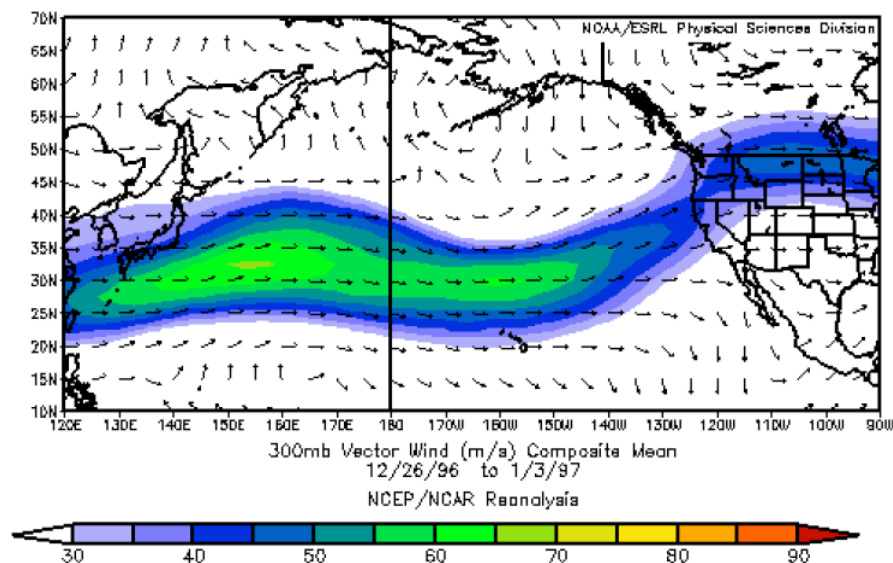


Figure 3.4 300 mb wind vector analysis for the 1997 event [NOAA, 1997]

A pineapple express-related influx of moisture played a key role in the generation of significant precipitation across the region. Two distinct moisture sources were evident from the composite mean precipitable water analysis (Figure 3.5) and the eta level 11 water vapor mixing ratio model results of the WRF (Figure 3.6) on January 1, 1997. The first source advected eastward from the western Pacific and the second one advected northward from near the equator between 150° and 160° West. These two moisture plumes merged near the Hawaiian Islands and shifted northeast toward the west coast of the United States. Composite daily mean precipitable water values just off the California coast exceeded 1.6 inches (40 mm) and peaked near 1.8 inches (45 mm) [NOAA, 1997].

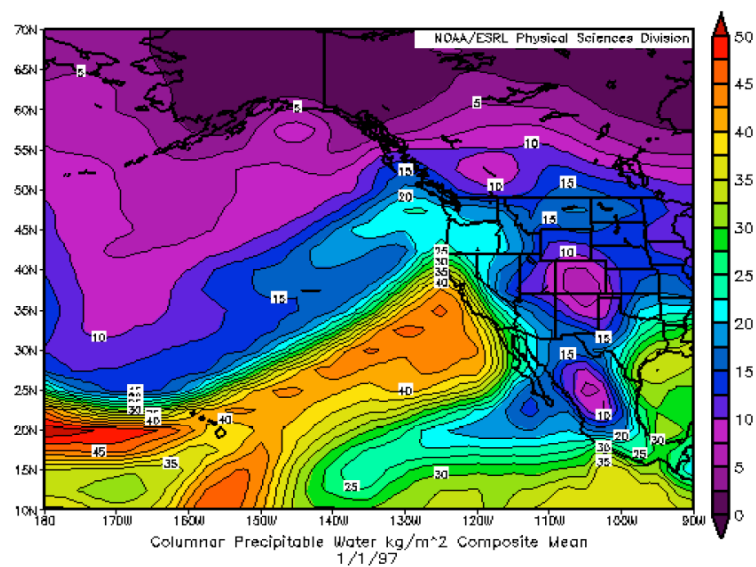


Figure 3.5 Composite mean precipitable water on January 1, 1997 [NOAA, 1997]

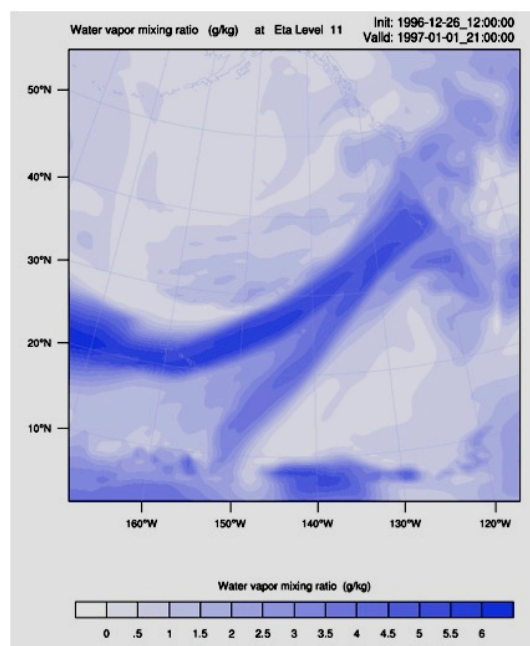


Figure 3.6 Water vapor mixing ratio results of the WRF at Eta Level 11 on January 1, 1997

3.3 Data

3.3.1 Model Data

In this research, the data from NCEP/NCAR Global Reanalysis Products (NNRP) [Kalnay *et al.*, 1996] were used to setup initial and boundary conditions of the WRF model. The data for this study are from the Research Data Archive (RDA), which is maintained by the Computational and Information Systems Laboratory (CISL) at the National Center for Atmospheric Research (NCAR). NCAR is sponsored by the National Science Foundation (NSF). The original data are available from the RDA (<http://dss.ucar.edu>) in dataset number ds090.0. Starting from 1948 and going forward continuously, 6 hourly output of the Global Reanalysis Model has the horizontal resolution of T62 (209 km) with 28 vertical sigma levels. Using the downscaling methods of the WRF, this resolution was refined to 3 km for this research.

3.3.2 Observation Data

Being an accumulative variable of NNRP, the output of precipitation rate is used for an example of 209 km resolution precipitation in order to show the resolution sensitivities of the WRF precipitation modeling results to different spatial grid resolutions, taken as 27 km, 9 km, and 3 km here. NexRAD radar data are also used for comparisons in order to show that model evaluations, based only on the radar data, are not sufficient since significant information could be missed if a storm hits the radar location, especially at highly orographic regions such as California.

Monthly precipitation modeling results of the WRF were compared to PRISM [www.prism.oregonstate.edu] data for December 1996. Using the 72 hr basin-averaged precipitation values of *USACE* [2005], 72-hr comparisons to the WRF-modeled

precipitation were performed. Performance investigations of the WRF, regarding point locations, rather than areal averages, have been done using hourly ground precipitation observations of California Data Exchange Center (CDEC) for the American River Basin. Grid-averaged precipitation output of the WRF was interpolated to the corresponding station locations of CDEC using bilinear interpolation method. The reliability of USACE data was also evaluated by means of these point-location data.

3.4 Calibration and Validation

1997 New Year's California Flood was chosen for the calibration study since it is the historically first ranked flood at the American River Basin, although it is ranked as the 7th in terms of 72-hr basin-averaged maximum precipitation as was discussed in the pineapple express section 3.2.1.

The probable maximum precipitation calculations generally generate 72-hr based curves for depth-duration-area and frequency-depth-duration analyses. According to the traditional method, these 72-hr curves are calculated based on basin averages. In order to make comparison with these curves, 72-hr maximum precipitation was chosen from the corresponding historical storm if the duration of that storm was longer than 72-hr. If the duration was shorter than that, the nearest maximum duration was used.

For calibration-validation (CV) purposes, the basin average maximum 72-hr precipitation results were analyzed in order to be consistent with the traditional method for comparison purposes. The hourly grid averaged precipitation output of the model were first interpolated into the basin for 1148 latitude and longitude points, defined by USGS for the American River Basin, using the bilinear interpolation method of CISL's NCAR Command Language (NCL). Then, the hourly areal average value of precipitation was obtained. From the

constructed time series, the maximum 72-hr basin averaged precipitation was finally determined.

Meanwhile, a significant disadvantage of applying maximum 72-hr basin averaged precipitation is that the watershed-averaged maximum 72-hr precipitation analysis cannot be assumed to be representative for all drainage basins, especially for the basins sitting in a complex topography as is the case of the American River Watershed in California. We believe that this approach was convenient in the time when there was no modeling technology available.

Point location analysis of maximum precipitation is more practical and realistic than that of areal-averages for design purposes, especially for California. That is, a dam or a levee can be constructed in a location, for instance a downstream where PMP has impact, where the average PMP value is not representative. Therefore, it is going to be shown that the proposed modeling approach here can also determine point PMP values accurately. It should be noted that although quantitative precipitation forecasting (QPF) for specific locations is a challenging problem in terms of both the magnitude and timing of a storm, it can be modeled to a degree of agreement with observations, so that it may be utilized for PMP estimates. More accurate QPF would lead to more accurate results in PMP estimation.

The CV procedure here was performed considering only the cumulus parameterization, cloud microphysics, and atmospheric boundary layer options (CMBL) of the WRF model assuming that these three physical processes play the major role in modeling of precipitation. As one might appreciate, testing all the physics and dynamics options would take excessive amount of time and data storage.

Based on the modeling experience of the author, eight combinations of the WRF physical parameterizations for California were chosen as shown in Table 3.1, for the calibration of the model. For instance, in microphysics section, WSM 3-class is chosen since it is expected to be physically less representative in the WSM microphysics families for California and Thompson scheme is selected to point out the best representation. Therefore, it is aimed to provide a rough range for precipitation. 72-hr maximum basin-averaged precipitation results of the WRF model show that Thompson microphysics-YSU boundary layer and Grell 3D ensemble cumulus parameterization combination of options is the best triplet option for modeling precipitation over the American River Watershed (Table 3.1), since 12.460 inches of precipitation is the closest to the precipitation observation of USACE (Table 3.2) which is 11.22 inches for the water year 1997.

Table 3.1 The WRF model physics option configurations for calibration purposes							
Name	Version	Microphysics	Cumulus	PBL	MP (in)	Max 72 hr Period	Total number of parameters calibrated
C7	V3.0.1.1	3. WSM 3-class	1. Kain-Fritsch	1. YSU	13.082	1996-12-31_02:00 1997-01-03_02:00	18
C8	V3.0.1.1	3. WSM 3-class	1. Kain-Fritsch	2. Mellor-Yamada-Janjic	14.601	1996-12-30_18:00 1997-01-02_18:00	17
C9	V3.0.1.1	3. WSM 3-class	5. Grell 3D	1. YSU	13.222	1996-12-30_19:00 1997-01-02_19:00	22
C10	V3.0.1.1	3. WSM 3-class	5. Grell 3D	2. Mellor-Yamada-Janjic	14.375	1996-12-30_18:00 1997-01-02_18:00	21
C16	V3.0.1.1	8. Thompson	1. Kain-Fritsch	1. YSU	13.107	1996-12-30_19:00 1997-01-02_19:00	23
C17	V3.0.1.1	8. Thompson	1. Kain-Fritsch	2. Mellor-Yamada-Janjic	13.918	1996-12-30_19:00 1997-01-02_19:00	22
C18	V3.0.1.1	8. Thompson	5. Grell 3D	1. YSU	12.460	1996-12-30_19:00 1997-01-02_19:00	27
C19	V3.0.1.1	8. Thompson	5. Grell 3D	2. Mellor-Yamada-Janjic	13.647	1996-12-30_19:00 1997-01-02_19:00	26

Table 3.2 72-hour maximum basin averaged precipitation of the American River Watershed observations vs. the WRF model simulations for validation purposes (USACE, 2005)

72-hour Storm (Storm date to include)				72-hour watershed-average precipitation (inches)				
Water Year	Month	Day	Year	GIS modified Thiessen	GIS Storm Analysis	Adopted Value	WRF	STA
1951	11	20	1950	11.80	12.46	12.46	10.29	0.46
1956	12	23	1955	14.02	13.81	13.81	13.08	0.04
1963I	10	13	1962	13.59	14.05	14.05	13.78	0.01
1963II	2	1	1963	12.65	11.39	11.39	9.59	0.34
1965	12	23	1964	12.90	12.47	12.47	15.00	0.43
1966	11	18	1965	4.48	-	4.48	3.08	0.63
1967	1	22	1967	7.53	7.05	7.05	7.72	0.06
1968	2	21	1968	3.50	-	3.50	4.29	0.15
1969	1	21	1969	10.3	10.34	10.34	5.85	3.44
1970	1	16	1970	6.74	6.46	6.46	4.14	1.30
1971	12	3	1970	5.72	-	5.72	6.15	0.03
1972	12	24	1971	4.70	-	4.70	3.95	0.14
1973	1	18	1973	5.35	-	5.35	6.22	0.12
1974	11	12	1973	5.84	6.20	6.20	7.39	0.19
1975	2	3	1975	4.49	-	4.49	7.08	0.95
1976	10	27	1975	2.96	-	2.96	2.02	0.44
1977	1	3	1977	3.33	-	3.33	2.71	0.14
1978	1	16	1978	5.98	-	5.98	7.10	0.18
1979	1	12	1979	5.14	-	5.14	4.73	0.03
1980	1	13	1980	9.67	9.94	9.94	8.06	0.44
1981	1	29	1981	6.92	6.37	6.37	6.52	0.00
1982	2	15	1982	7.78	8.17	8.17	8.88	0.06
1983	12	22	1982	7.77	8.24	8.24	7.29	0.12
1984	12	26	1983	6.24	6.04	6.04	7.99	0.48
1985	2	9	1985	4.44	-	4.44	5.39	0.17
1986	2	18	1986	13.75	13.99	13.99	12.54	0.17
1987	2	13	1987	4.14	-	4.14	3.26	0.24
1988	4	21	1988	3.03	-	3.03	3.11	0.00
1989	11	24	1988	5.33	4.91	4.91	6.76	0.51
1990	11	27	1989	5.15	4.44	4.44	2.68	1.16
1991	3	3	1991	6.59	-	6.59	7.21	0.05
1992	2	16	1992	3.61	-	3.61	3.79	0.01
1993	12	10	1992	6.51	7.19	7.19	5.41	0.59
1994	2	19	1994	3.27	-	3.27	3.94	0.11
1995	3	10	1995	7.59	7.93	7.93	9.80	0.36
1996	12	13	1995	7.64	7.88	7.88	7.10	0.09
1997	1	2	1997	11.4	11.22	11.22	11.48	0.01
1998	1	12	1998	5.16	-	5.16	4.36	0.15
1999	2	8	1999	8.42	8.41	8.41	9.15	0.06
2000	2	14	2000	7.40	-	7.40	7.14	0.01
2001	2	11	2001	3.41	-	3.41	3.80	0.04
2002	12	3	2001	4.16	-	4.16	4.30	0.00
								χ^2 13.88

The first 7 columns of Table 3.2 are adapted from *USACE* [2005]. In the first 4 columns, ending dates of 42 historical extreme precipitation events are presented. Columns 5 and 6 are the results of two different methods; GIS-Modified Thiessen approach and spatial analysis of storms using GIS-based methods, for 72-hr basin averaged maximum precipitation. *USACE* [2005] used GIS-based methods for spatial analysis of storms in order to interpolate precipitation data accurately between stations, which are located in mountainous watershed. GIS-Modified Thiessen approach is applied, on the other hand, for the events that have smaller annual maxima [*USACE*, 2005]. In column 7th of Table 3.2, adopted values are determined as the GIS storm analysis value, if no value is available for this method, then the value of Thiessen method is selected as the adopted value. In the next column 72-hr basin averaged maximum precipitation values of the WRF is presented (Table 3.2, column 8). In the 9th column, statistic (STA) denotes the individual scale deviation value as shown on the right hand side of equation 3.1 within the summation sign. That is, smaller STA values indicate a better model performance for each event. In the right lower corner of Table 3.2, χ^2 value (Equation 3.1), which is the summation of STA values is shown.

Here, only the precipitation amounts were compared to decide the best options, since hourly-based timing information is not available from *USACE* [2005]. Using these best triple options, 42 simulations were performed, and the Chi-square goodness-of-fit test was applied to comparisons between the WRF model-estimated 72-hour maximum watershed-averaged precipitation over the American River Watershed versus the corresponding *USACE*-provided observations in order to examine the hypothesis that the WRF model can be used in the determination of areally-averaged PMP estimates for the American River Watershed.

Chi-square goodness-of-fit test [Guttman *et al.*, 1982] is used to compare observed maximum 72-hr basin- averaged precipitation (OBS) to its modeled (MOD) counterpart;

$$\chi^2 = \sum_{i=1}^k \frac{(OBS_i - MOD_i)^2}{MOD_i} \quad (3.1)$$

and, using the observed versus modeled values for the 42 historical cases, it is found from equation 3.1 that $\chi^2 = 13.88$ (Table 3.2).

If the test is performed at the $100\alpha\%$ level of significance, the observed value of χ^2 is considered to be significant at this level if $\chi^2 > \chi_{k-1, \alpha}^2$; that is, the hypothesis will be rejected. The number of degrees of freedom, $m = k - 1$, involved in applying the chi-square test is $42 - 1 = 41$, using the fact that $k = 42$ (it is the number of historical extreme precipitation events being considered) for the studied case and 5% significance level has been chosen, thus $\alpha = 0.05$. Consulting the Percentage Points of the χ_m^2 Distribution table of Guttman *et. al* [1982], the upper 5% significance point was found to be $\chi_{41;0.05}^2 = 55.7585$. As a result, $\chi^2 < \chi_{41;0.05}^2$. Hence, at the 5% level of significance, the hypothesis that the WRF model can be used in the determination of areal-averaged PMP estimates for the American River Watershed, is accepted.

As was previously discussed, the reliability of the model approach for point PMP calculations rather than areal averages was also examined. This time it was hypothesized that the WRF model can be used in the determination of PMP for the American River

Watershed. For each station chi-square goodness-of-fit tests were performed. If any of the tests failed, the hypothesis was rejected for the American River Watershed. 13 ground base stations that have hourly precipitation data, were considered in this analysis, as shown in Figure 3.7 and Table 3.3. In Figure 3.7, the stations are shown with numbers, which are presented in the first column of Table 3.3.

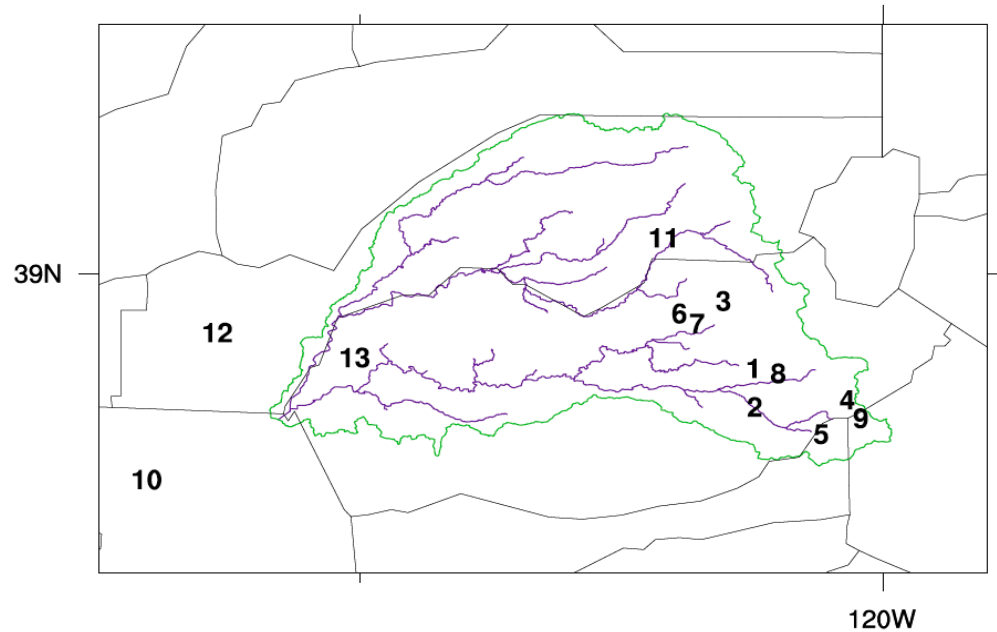


Figure 3.7 The map of the American River Watershed and precipitation stations

Table 3.3 Precipitation observation stations						
NO	The American River STATIONS	ID	Elev	Latitude	Longitude	County
1	ALPHA (SMUD)	ALP	7600	38.805	120.215	EL DORADO
2	OWENS CAMP	OWC	4500	38.733	120.245	EL DORADO
3	VAN VLECK	VVL	6700	38.945	120.305	EL DORADO
4	SCHNEIDERS	SCN	8750	38.747	120.068	EL DORADO
5	SILVER LAKE	SIL	7100	38.678	120.118	EL DORADO
6	ROBBS SADDLE	RBB	5900	38.912	120.378	EL DORADO
7	ROBBS POWERHOUSE	RBP	5150	38.903	120.375	EL DORADO
8	BETA	BTA	7600	38.8	120.2	EL DORADO
9	CAPLES LAKE (DWR)	CAP	8000	38.71	120.042	ALPINE
10	HURLEY	HUR	35	38.587	121.407	SACRAMENTO
11	HELL HOLE (USFS)	HLH	4580	39.0717	120.4217	PLACER
12	LINCOLN	LCN	200	38.882	121.272	PLACER
13	PILOT HILL (CDF)	PIH	1200	38.8317	121.0092	EL DORADO

The grid area-averaged model precipitation results were interpolated to the locations of these stations using bilinear interpolation. Station-based precipitation comparisons are presented in Table 3.4.

Table 3.4 Precipitation observations vs. the WRF precipitation (inches)										
ALP										
Water Year	Year	Month	Day	Hour	OBS	Month	Day	Hour	WRF	STA
1996	1995	12	13	2300	5.04	12	15	600	6.09	0.18
1997	1997	1	3	400	9.05	1	3	600	7.07	0.55
1998	1998	1	13	2000	6.10	1	13	400	3.52	1.89
1999	1999	2	9	1600	7.04	2	9	1600	7.56	0.04
2000	2000	2	14	2100	4.75	2	14	1700	4.63	0.00
2001	2001	2	12	1800	2.66	2	12	600	2.71	0.00
OWC										
Water Year	Year	Month	Day	Hour	OBS	Month	Day	Hour	WRF	STA
1997	1997	1	3	100	9.31	1	2	1900	12.46	0.80
1998	1998	1	12	1800	2.09	1	12	2200	2.47	0.06
1999	1999	2	9	800	5.63	2	9	1600	7.87	0.64
2000	2000	2	15	1500	3.71	2	14	1700	6.69	1.33
VVL										
Water Year	Year	Month	Day	Hour	OBS	Month	Day	Hour	WRF	STA
1993	1992	12	9	1600	6.53	12	11	1300	7.77	0.20
1994	1994	2	20	300	3.73	2	19	2200	4.63	0.18
1995	1995	3	12	0	9.86	3	11	1100	12.26	0.47
1996	1995	12	12	2100	1.47	12	14	100	9.22	6.51
1998	1998	1	13	1500	6.54	1	13	400	6.55	0.00
1999	1999	2	9	1800	12.37	2	9	1500	13.91	0.17
2000	2000	2	14	1700	8.50	2	14	1700	8.18	0.01
2001	2001	2	12	300	4.92	2	11	2300	4.70	0.01
SCN										
Water Year	Year	Month	Day	Hour	OBS	Month	Day	Hour	WRF	STA
1996	1995	12	13	2200	6.71	12	14	100	7.33	0.05
1998	1998	1	13	1400	4.24	1	12	2200	2.82	0.72
1999	1999	2	10	400	2.23	2	9	1600	9.13	5.21
2000	2000	2	14	1900	4.81	2	14	1700	6.97	0.67
2001	2001	2	12	1500	3.05	2	12	0	3.92	0.19
SIL										
Water Year	Year	Month	Day	Hour	OBS	Month	Day	Hour	WRF	STA
1993	1992	12	9	1600	6.53	12	11	1500	6.79	0.01
1994	1994	2	20	300	3.73	2	20	200	5.38	0.51
1995	1995	3	12	0	9.86	3	11	1000	14.11	1.28
1996	1995	12	14	0	8.26	12	14	100	11.20	0.77
1998	1998	1	12	1800	2.40	1	12	2100	3.56	0.38
1999	1999	2	9	1400	6.66	2	9	1600	12.19	2.51
2000	2000	2	14	1500	5.33	2	14	1700	8.40	1.12
2001	2001	2	11	1900	3.07	2	12	0	4.58	0.50
RBB										
Water Year	Year	Month	Day	Hour	OBS	Month	Day	Hour	WRF	STA
1996	1995	12	14	800	8.37	12	14	100	7.80	0.04

1998	1998	1	13	1500	6.22	1	13	400	4.89	0.36
1999	1999	2	9	1900	8.90	2	9	1400	9.80	0.08
2000	2000	2	14	1700	7.04	2	14	1700	6.42	0.06
2001	2001	2	12	400	3.55	2	11	2300	3.75	0.01
RBP										
Water Year	Year	Month	Day	Hour	OBS	Month	Day	Hour	WRF	STA
1996	1995	12	13	2100	8.05	12	14	100	7.48	0.04
1998	1998	1	13	1400	6.37	1	13	400	4.91	0.43
1999	1999	2	9	1800	9.23	2	9	1400	9.88	0.04
2000	2000	2	14	1700	7.14	2	14	1700	6.42	0.08
2001	2001	2	12	1200	3.73	2	11	2300	3.70	0.00
BTA										
Water Year	Year	Month	Day	Hour	OBS	Month	Day	Hour	WRF	STA
1985	1985	2	10	1200	3.20	2	10	300	4.68	0.47
1986	1986	2	18	400	10.64	2	17	200	10.07	0.03
1987	1987	2	13	2300	3.84	2	14	400	1.71	2.65
1989	1988	11	25	900	4.16	11	24	1500	5.42	0.29
1990	1989	11	26	1700	3.64	11	26	1700	2.26	0.84
1993	1992	12	11	1600	5.60	12	11	1400	5.42	0.01
1994	1994	2	20	1500	3.04	2	20	200	3.07	0.00
1995	1995	3	12	300	5.44	3	10	1800	3.02	1.95
1996	1995	12	14	600	4.60	12	15	600	6.14	0.39
1997	1997	1	3	300	9.64	1	3	600	7.29	0.76
1998	1998	1	13	1900	5.00	1	13	300	3.43	0.72
2001	2001	2	12	1800	2.12	2	11	2300	2.78	0.16
CAP										
Water Year	Year	Month	Day	Hour	OBS	Month	Day	Hour	WRF	STA
1992	1992	2	15	700	2.80	2	15	1000	5.19	1.10
1993	1992	12	9	1400	6.40	12	11	15	6.57	0.00
1994	1994	2	20	700	3.47	2	19	18	5.42	0.70
1995	1995	3	12	200	8.66	3	11	1000	14.54	2.38
1996	1995	12	14	1500	7.46	12	14	100	10.11	0.69
1997	1997	1	2	1800	8.93	1	2	1900	13.32	1.45
1998	1998	1	13	1400	2.14	1	12	2100	3.01	0.25
HUR										
Water Year	Year	Month	Day	Hour	OBS	Month	Day	Hour	WRF	STA
1996	1995	12	14	0	4.27	12	13	2200	3.40	0.22
1997	1997	1	1	2100	2.36	1	2	1700	6.26	2.43
1998	1998	1	12	2000	1.63	1	12	1700	2.00	0.07
1999	1999	2	9	1800	1.75	2	9	1100	3.94	1.22
2000	2000	2	14	1300	3.40	2	14	1400	2.76	0.15
2001	2001	2	11	2000	2.38	2	11	2000	1.83	0.17
2002	2001	12	3	1600	0.93	12	3	1500	1.25	0.08
HLH										
Water Year	Year	Month	Day	Hour	OBS	Month	Day	Hour	WRF	STA
1993	1992	12	10	1600	4.12	12	11	1100	6.25	0.72
1994	1994	2	19	1000	0.26	2	19	1700	4.19	3.69
1997	1997	1	2	1300	8.98	1	3	600	11.58	0.58
1998	1998	1	12	1400	5.98	1	13	300	5.50	0.04
1999	1999	2	9	2000	10.69	2	9	1400	10.07	0.04
2000	2000	2	14	1700	7.85	2	14	1600	7.52	0.01
2001	2001	2	11	1800	3.35	2	11	2300	4.62	0.35

2002	2001	12	3	1100	6.64	12	3	100	4.35	1.21
LCN										
Water Year	Year	Month	Day	Hour	OBS	Month	Day	Hour	WRF	STA
1993	1992	12	11	1300	0.13	12	9	1700	2.05	1.80
1994	1994	2	20	100	1.29	2	19	1800	3.02	0.99
1995	1995	3	11	2100	2.85	3	11	400	3.52	0.13
1996	1995	12	14	0	3.27	12	15	600	3.09	0.01
1997	1997	1	2	1100	0.18	1	2	1700	4.97	4.62
1998	1998	1	12	1500	2.10	1	12	1700	2.52	0.07
1999	1999	2	9	900	1.70	2	9	1100	2.84	0.46
2000	2000	2	13	900	3.47	2	14	1400	3.55	0.00
2001	2001	2	12	1200	1.34	2	11	2000	1.51	0.02
2002	2001	12	3	1500	1.14	12	2	100	1.84	0.27
PIH										
Water Year	Year	Month	Day	Hour	OBS	Month	Day	Hour	WRF	STA
1995	1995	3	10	100	0.20	3	11	1100	5.02	4.63
1996	1995	12	13	600	0.41	12	15	1600	3.03	2.26
1997	1997	1	2	2300	5.09	1	2	1800	4.72	0.03
1998	1998	1	12	1600	4.58	1	12	2100	3.10	0.71
1999	1999	2	9	1000	4.44	2	9	1100	4.77	0.02
2000	2000	2	14	1100	6.27	2	14	1500	4.58	0.63
2001	2001	2	11	1500	2.44	2	11	2100	2.31	0.01
2002	2001	12	2	700	0.47	12	2	100	1.78	0.96

As may be seen from Table 3.5, all of the chi-square goodness-of-fit tests for these stations were passed at the 5% level of significance. Thus, the hypothesis that the WRF model can be used in the determination of PMP for the American River Watershed, was accepted at 5% significance level.

Table 3.5 Station based Chi-square goodness-of-fit test					
Station	STA	TABLE	Station	STA	TABLE
ALP	2.66	<9.49	CAP	6.58	<11.07
OWC	2.82	<5.99	RBB	0.56	<7.81
VVL	7.55	<12.59	RBP	0.60	<7.81
LCN	8.35	<15.5	SCN	6.84	<7.81
PIH	9.24	<12.59	SIL	7.07	<12.59
HUR	4.34	<11.07	HLH	6.65	<12.59
BTA	8.27	<18.31			

3.5 Sensitivity Analysis

As was mentioned in the literature review section, *Zhao et al.* [1997], *Abbs* [1999], and *Cotton et al.* [2002] suggested that numerical weather prediction (NWP) models can be useful tools for PMP calculations. On the other hand, there is a contradictory point of view that NWP models can be used in a limited way for PMP studies, since precipitation modeling results may be too sensitive to model initialization and parameterization [*Chen*, 2005]. In order to investigate this issue, detailed sensitivity analyses were performed in this study to show the degree of model sensitivity and the methods to overcome this problem, so that one can eliminate the argument of sensitivity problem in the use of NWP models for PMP estimations. Sensitivity analyses were performed in order to assess the individual importance of the cumulus parameterization, cloud microphysics and atmospheric boundary layer options (CMBLs) on of the estimation area-averaged precipitation and its duration. This approach allows one to evaluate which parameterization uncertainty is the most significant. It was assumed that the Thompson-Grell 3D-YSU (TGY) triple option combination, found in the calibration section, is the best option among all CMBLs. Accordingly, a subset of physical options with respect to the TGY triple was setup in order to eliminate the rest of the combinations of the physical parameterizations. In here, the microphysics, cumulus parameterization, and boundary layer options are tested with fixed parameters. Since the TGY option passed the statistical test for the ARW of California, parameters are not varied to see their effect on precipitation. It is important to note that parameters are needed to be tuned with an additional calibration and validation step for an interested domain if any physics combination do not pass a statistical test.

Table 3.6 SET-I The WRF model physics option configurations- Sensitivity analyses of MP						
Name	Version	Microphysics	Cumulus	PBL	MP (in)	Max 72 hr Period
M1	V3.1.1	1. No Microphysics	5. Grell 3D	1. YSU	0	-
M2	V3.1.1	1. Kessler	5. Grell 3D	1. YSU	13.956	1996-12-31_06:00 1997-01-03_06:00
M3	V3.1.1	2. Lin et al.	5. Grell 3D	1. YSU	15.016	1996-12-31_02:00 1997-01-03_02:00
M4	V3.1.1	3. WSM 3-class	5. Grell 3D	1. YSU	13.179	1996-12-31_06:00 1997-01-03_06:00
M5	V3.1.1	4. WSM 5-class	5. Grell 3D	1. YSU	11.982	1996-12-31_06:00 1997-01-03_06:00
M6	V3.1.1	5. Ferrier	5. Grell 3D	1. YSU	13.011	1996-12-31_02:00 1997-01-03_02:00
M7	V3.1.1	6. WSM 6-class	5. Grell 3D	1. YSU	12.900	1996-12-31_02:00 1997-01-03_02:00
M8	V3.1.1	7. Goddard GCE	5. Grell 3D	1. YSU	10.980	1996-12-31_03:00 1997-01-03_03:00
M9	V3.1.1	8. Thompson	5. Grell 3D	1. YSU	11.484	1996-12-31_00:00 1997-01-03_00:00
M10	V3.1.1	10. Morrison	5. Grell 3D	1. YSU	10.751	1996-12-30_18:00 1997-01-02_18:00
M11	V3.1.1	14. WDM 5-class	5. Grell 3D	1. YSU	11.809	1996-12-31_06:00 1997-01-03_06:00
M12	V3.1.1	6. WSM 6-class	5. Grell 3D	1. YSU	13.389	1996-12-31_02:00 1997-01-03_02:00
M13	V3.1.1	98. Thompson (from V3.0)	5. Grell 3D	1. YSU	12.587	1996-12-30_19:00 1997-01-02_19:00

In the first set, the Grell 3D ensemble and YSU schemes were kept constant and the 1997 extreme precipitation event case was simulated for all microphysics parameterization options (Table 3.6). In the second set, the Thompson and Grell 3D ensemble schemes were fixed, altering all planetary boundary layer schemes (Table 3.7). In the third set, Thompson and YSU schemes were fixed, varying all cumulus parameterization schemes (Table 3.8).

Table 3.7 SET-II The WRF model physics option configurations- Sensitivity analyses of PBL						
Name	Version	Microphysics	Cumulus	PBL	MP (in)	Max 72 hr Period
B1	V3.1.1	8. Thompson	5. Grell 3D	0. No Boundary Layer	18.571	1996-12-30_12:00 1997-01-02_12:00
B2	V3.1.1	8. Thompson	5. Grell 3D	1. YSU	11.484	1996-12-31_00:00 1997-01-03_00:00
B3	V3.1.1	8. Thompson	5. Grell 3D	2. Mellor-Yamada-Janjic	12.323	1996-12-30_18:00 1997-01-02_18:00
B4	V3.1.1	8. Thompson	5. Grell 3D	4. Quasi-Normal Scale Elimination	12.723	1996-12-30_18:00 1997-01-02_18:00
B5	V3.1.1	8. Thompson	5. Grell 3D	5. MYNN 2.5 Level TKE	12.301	1996-12-30_18:00 1997-01-02_18:00
B6	V3.1.1	8. Thompson	5. Grell 3D	6. MYNN 3rd Level TKE	12.222	1996-12-31_06:00 1997-01-03_06:00
B7	V3.1.1	8. Thompson	5. Grell 3D	7. ACM2 (Pleim)	12.897	1996-12-30_18:00 1997-01-02_18:00
B8	V3.1.1	8. Thompson	5. Grell 3D	8. Bougeault and Lacarre	11.622	1996-12-31_06:00 1997-01-03_06:00
B9	V3.1.1	8. Thompson	5. Grell 3D	99. MRF	12.061	1996-12-31_03:00 1997-01-03_03:00

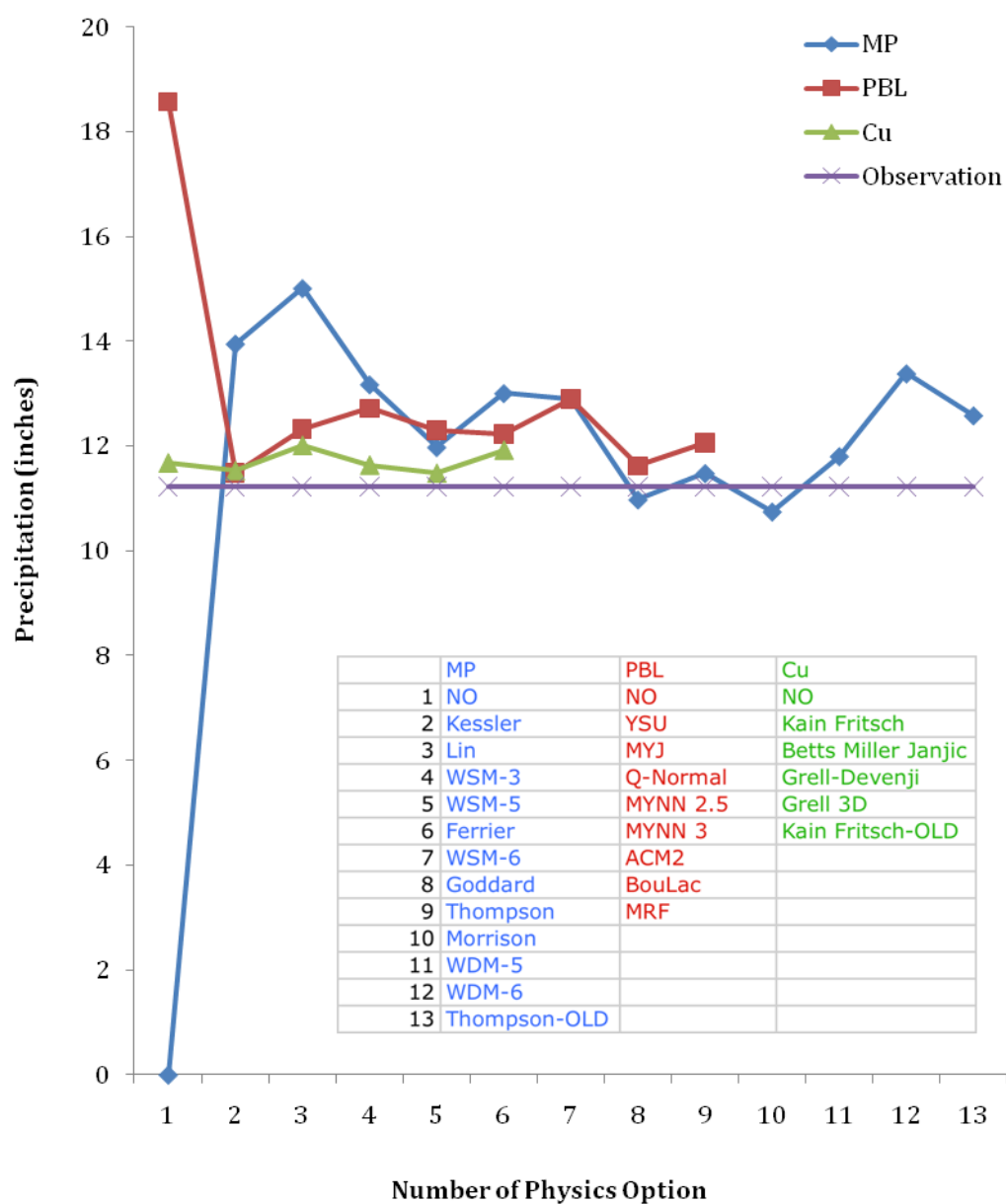
Table 3.8 SET-III The WRF model physics option configurations- Sensitivity analyses of CU						
Name	Version	Microphysics	Cumulus	PBL	MP (in)	Max 72 hr Period
C1	V3.1.1	8.Thompson	0. no cumulus	1. YSU	11.676	1996-12-31_03:00 1997-01-03_03:00
C2	V3.1.1	8.Thompson	1. Kain-Fritsch (new eta)	1. YSU	11.527	1996-12-30_19:00 1997-01-02_19:00
C3	V3.1.1	8.Thompson	2. Betts-Miller-Janjic	1. YSU	12.007	1996-12-30_19:00 1997-01-02_19:00
C4	V3.1.1	8.Thompson	3. Grell-Devenyi ensemble	1. YSU	11.635	1996-12-31_06:00 1997-01-03_06:00
C5	V3.1.1	8. Thompson	5. Grell 3D	1. YSU	11.484	1996-12-31_00:00 1997-01-03_00:00
C6	V3.1.1	8.Thompson	99. Previous Kain-Fritsch	1. YSU	11.918	1996-12-30_19:00 1997-01-02_19:00

Upon examination of the Tables 3.6-3.8, the model simulation results imply that precipitation is most sensitive to the microphysics option and less sensitive to cumulus parameterization. Yet, storm timing is quite sensitive to all physics options. Figure 3.8 shows

the overall sensitivity distributions of the WRF model physics options. As expected, no precipitation is produced if a microphysics option is turned off. If a planetary boundary layer option is turned off, on the other hand, obtained precipitation is spurious. Therefore, it is a necessity that these two model physics are used.

This sensitivity analysis, based upon a subset of the WRF parameterizations, shows that the maximum deviation from the actual maximum precipitation is about 3.5 inches due to the microphysics option sensitivities. Although one might assume that 3.5-inches variation may be acceptable, we suggest that a calibration and validation study is needed before a NWP model is applied for PMP estimates over a watershed. Such a calibration-validation procedure will be adequate to reduce uncertainty regarding model sensitivities.

Figure 3.8 WRF Physics option sensitivities to precipitation



3.6 Chapter Conclusions

The results of calibration and validation of the WRF model, based on 52 years of extreme precipitation observations (42 historical extreme events during this period), regarding both areally-averaged and local precipitation, show that the WRF model is reliable for PMP estimation studies. As a result of this calibration and validation study, as shown in Tables 3.1 and 3.2, Thompson microphysics-Grell 3D ensemble cumulus-YSU boundary layer physics is chosen as the best triplet option combination for the American River Watershed modeling for the estimation of both precipitation amounts and occurrences times. Since, 12.460 inches of precipitation is the closest to the precipitation observation of USACE (Table 3.2) which is 11.22 inches for the water year 1997. This conclusion is also supported by the results of the performed sensitivity analyses (Figure 3.8 and Tables 3.6, 3.7, and 3.8). Therefore, the first steps of the new method, developed here, may be stated as follows:

- ✓ Determining the atmospheric systems, which cause maximum precipitation in the domain of interest;
- ✓ Gathering a sufficiently large number of historical maximum precipitation events for the study domain in order to be able to make sound statistical inferences;
- ✓ Modeling the most severe historical event for calibration of the model physics;
- ✓ Modeling of all observed historical extreme precipitation events with the calibrated WRF model physics options for the validation of the model physics;

- ✓ Applying sensitivity analyses as a control mechanism of the validation and calibration procedure and as the determination of physics parameterization sensitivities of the model used on precipitation.

Chapter IV

Extreme Precipitation Estimation

In this chapter, possible physically based methods for precipitation maximization are investigated. The principal goal is to determine the key parameters on reaching extreme precipitation and to provide a physical basis for that. Physical basis is emphasized, since it is possible that a numerical weather prediction model can simulate very extreme conditions, although the results physically would not make any sense, as in the case of traditional PMP calculations. For instance, a hurricane hitting northwestern California, which has never happened in history, can be modeled. Thereby, an extremely high precipitation maximum could be obtained. Ironically, one might then argue that all hydraulic structures should be designed based on such results, since we do not know what shall happen under the circumstances of climate change. Therefore it is important to note that the proposed upper limit of maximum precipitation must be realistic, reflecting the real physical circumstances of the particular region where the PMP estimates are being sought. Hence, any atmospheric circumstances, that were not observed in the historical extreme events or are not realistically possible to happen over the American River Watershed, are not simulated in this study. Therefore, the aim here is to discuss all possible maximum conditions for the domain of interest, then to discuss their probabilities based on historical records. This approach enables one to understand the current maximum possible conditions, and would further be beneficial for the investigation of climate change effects on extreme precipitation. Although the climate change effect on precipitation is only marginally considered here, those results may constitute a starting point for climate change studies related to extreme events.

In order to maximize precipitation, first the pineapple express effect and then the role of key parameters on maximum precipitation shall be considered here. Thereafter, the interactions of these parameters with each other shall be distinguished by perturbing the initial and boundary conditions of the domains of interest. Finally, all these different combinations that caused maximum precipitation shall be combined in order to determine an upper limit for maximum precipitation, which will be assumed as the physical upper bound of probable maximum precipitation.

4.1 Pineapple Express Effect

It was mentioned in Chapter I that major floods in California are caused by the pineapple express, which is basically a path of an extensive amount of moisture entering California, approximately starting from Hawaiian Islands. Although the reasons of the pineapple express occurrences are not exactly known, it is known that it is a consequence of tropical cyclones driven by high and low systems and jet streams over eastern Pacific. Deferring the investigation of the starting mechanism of this phenomenon to another study, the pineapple express behavior is examined here with the central questions of whether all maximum precipitation events are caused by the pineapple express and every pineapple express brings maximum precipitation to California.

As was previously discussed, 42 historical flood events that happened at the American River Watershed are analyzed. If the pineapple express phenomenon is observed for each historical flood event for the 42 historical extreme precipitation events from 1950 to 2002, it will be assumed that all maximum precipitation occurrences that rendered those historical flood events are caused by the pineapple express event. In order to validate this assumption, precipitable water, a vertical integration of specific humidity as a function of pressure, is

used to diagnose the pineapple express. The pineapple express events corresponding to 42 flood events, in which occurred in between 1950 and 2002, are presented in Figure 4.1. A Pacific domain, larger than our model setup, was chosen so that one can evaluate the position of the pineapple express.

Based upon the precipitable water analysis of all 42 historical events, shown in Figure 4.1, the pineapple express phenomenon is observed for each historical flood event for the 42 historical extreme precipitation events from 1950 to 2002 without any exception. Therefore, it is assumed that all maximum precipitation occurrences that rendered those historical flood events are caused by the pineapple express event over the American River Watershed.

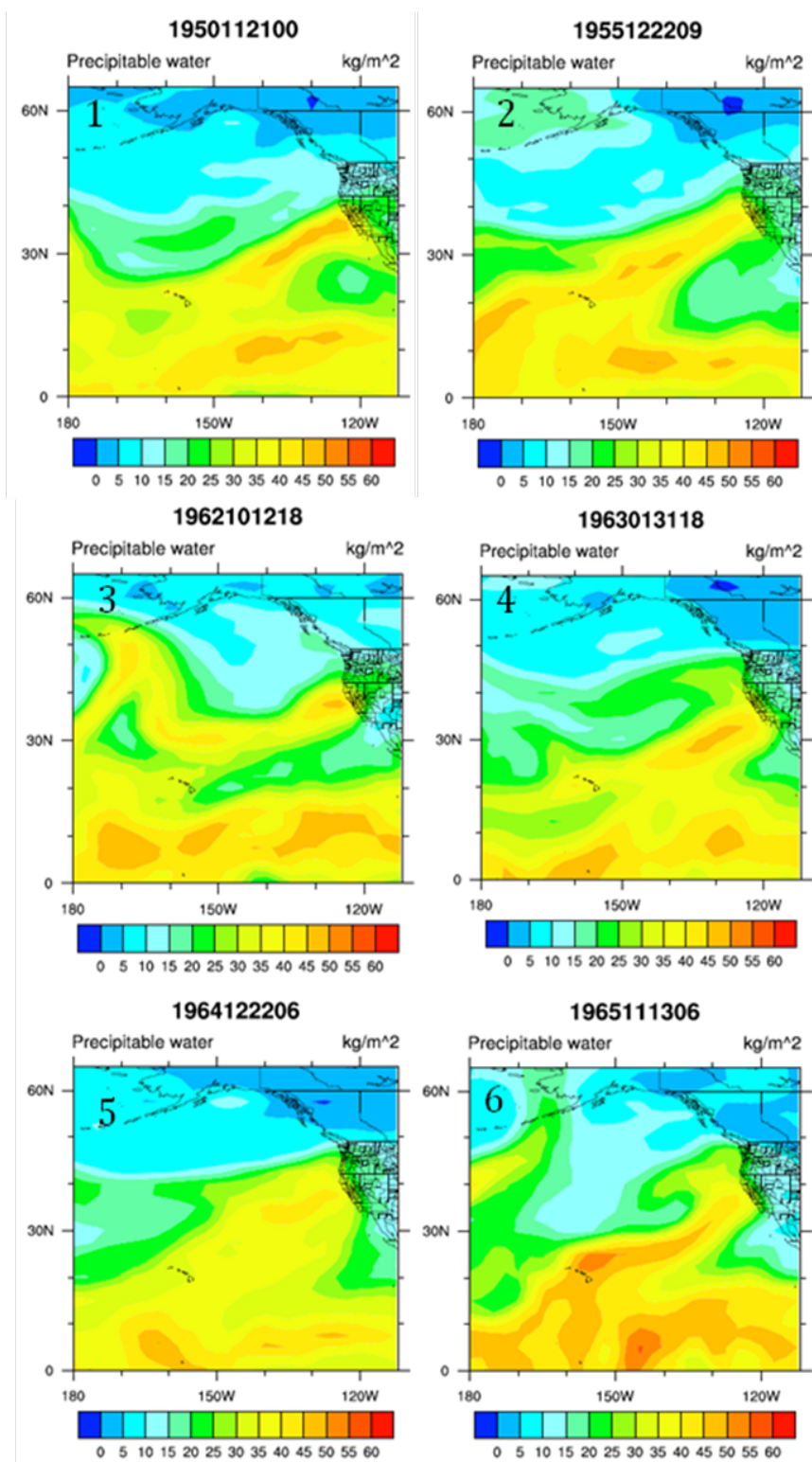


Figure 4.1 Pineapple express events that caused extreme precipitation and flood

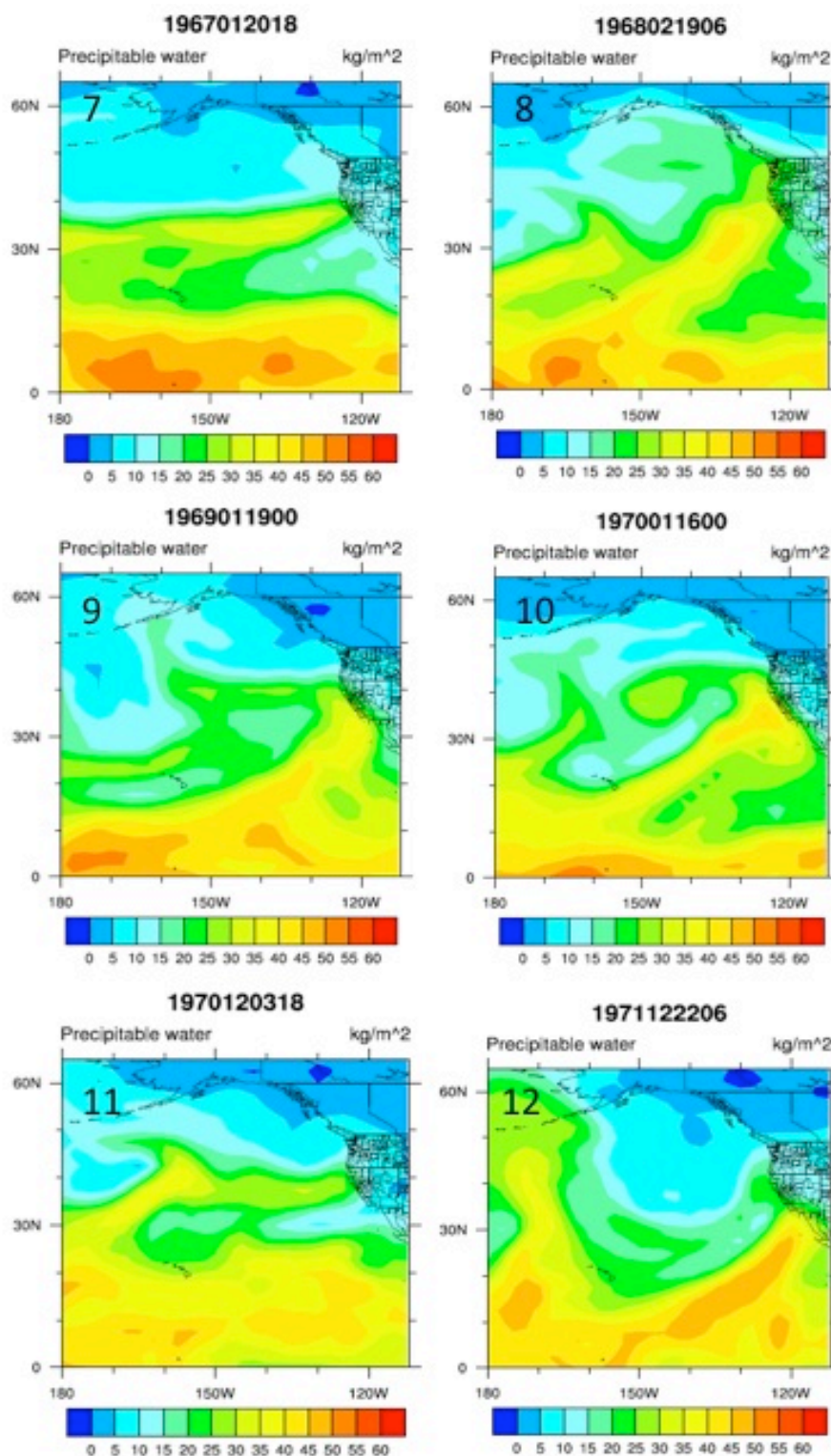


Figure 4.1 Pineapple express events that caused extreme precipitation and flood (continued)

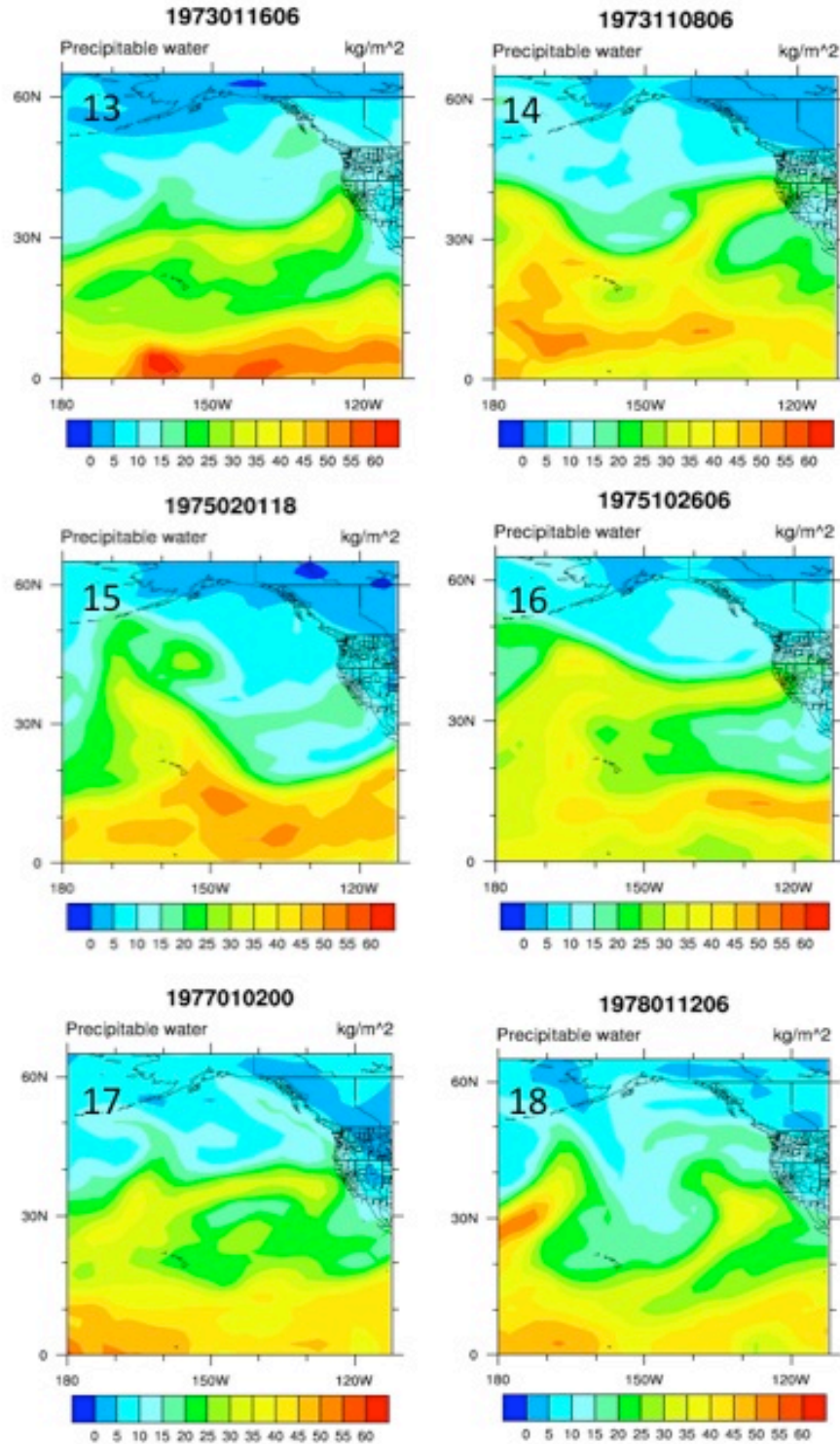


Figure 4.1 Pineapple express events that caused extreme precipitation and flood (continued)

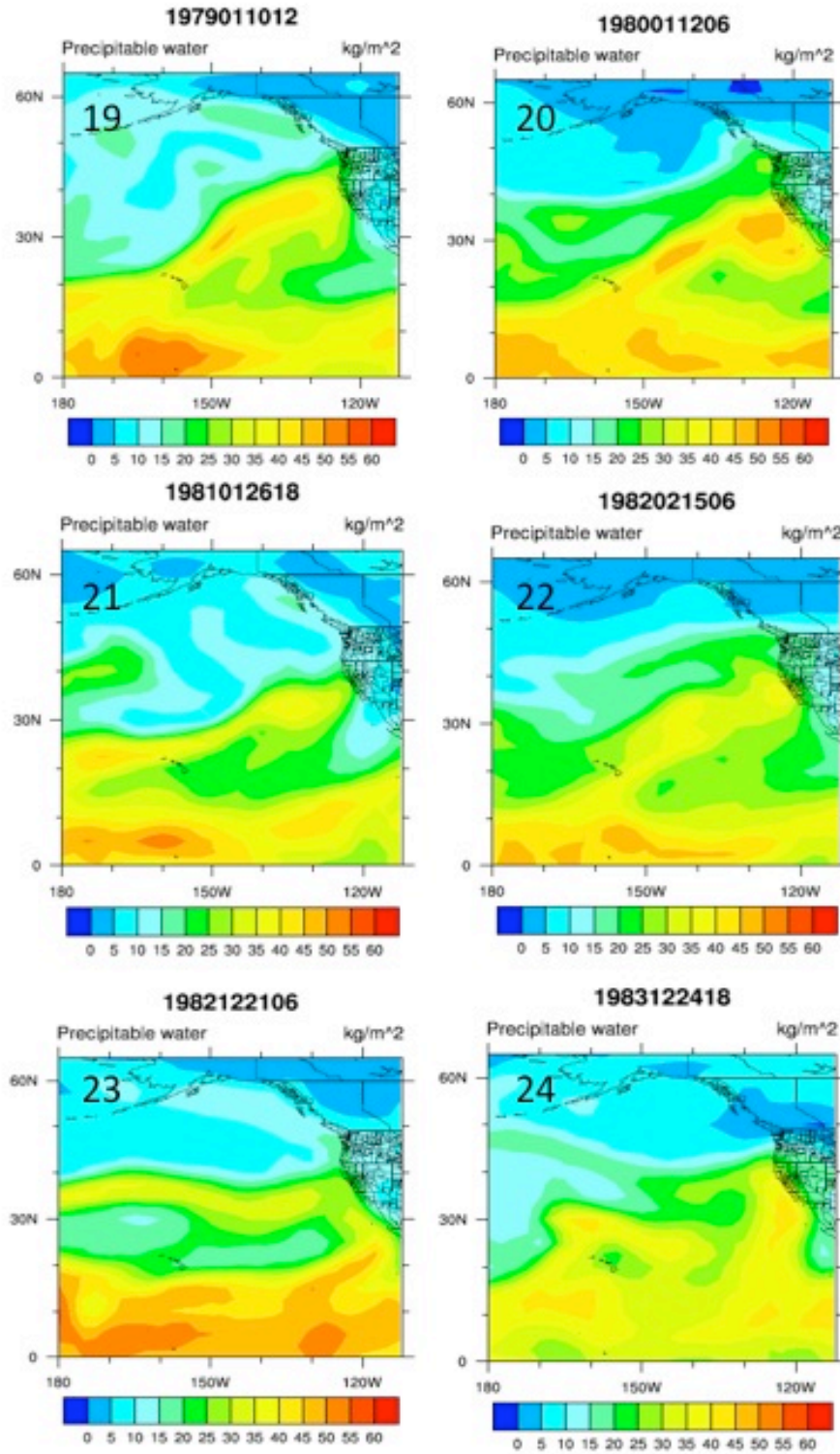


Figure 4.1 Pineapple express events that caused extreme precipitation and flood (continued)

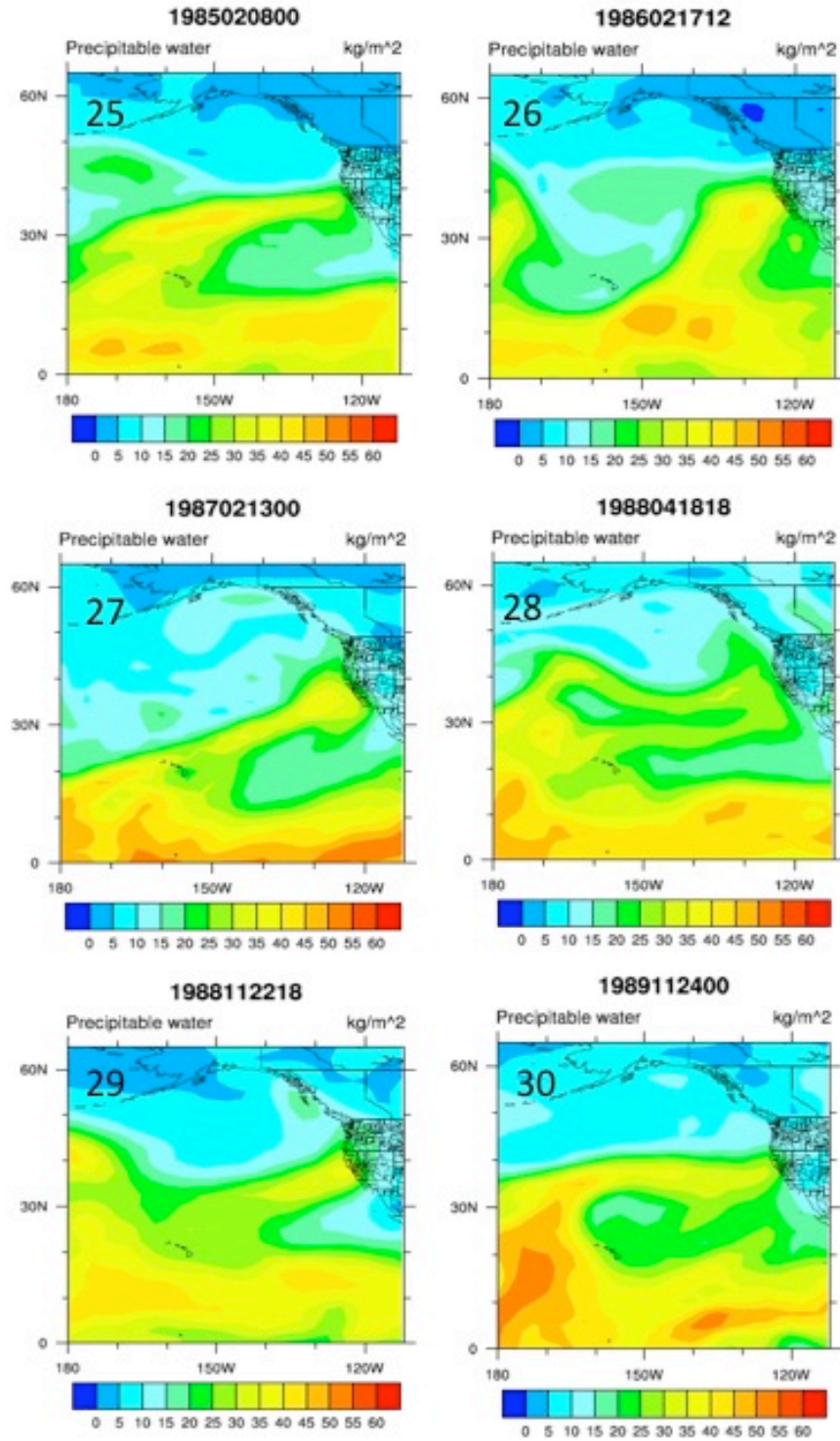


Figure 4.1 Pineapple express events that caused extreme precipitation and flood (continued)

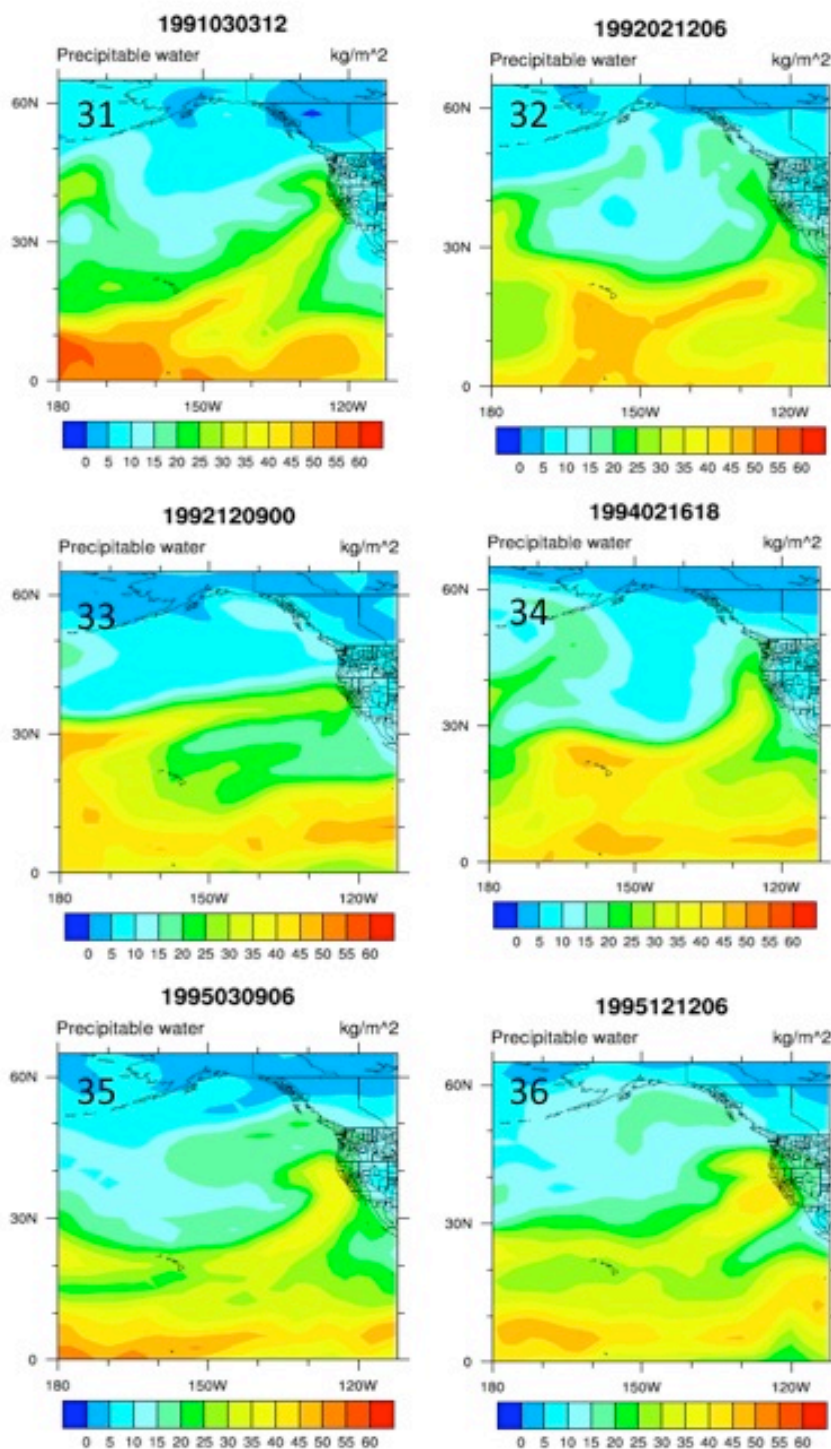


Figure 4.1 Pineapple express events that caused extreme precipitation and flood (continued)

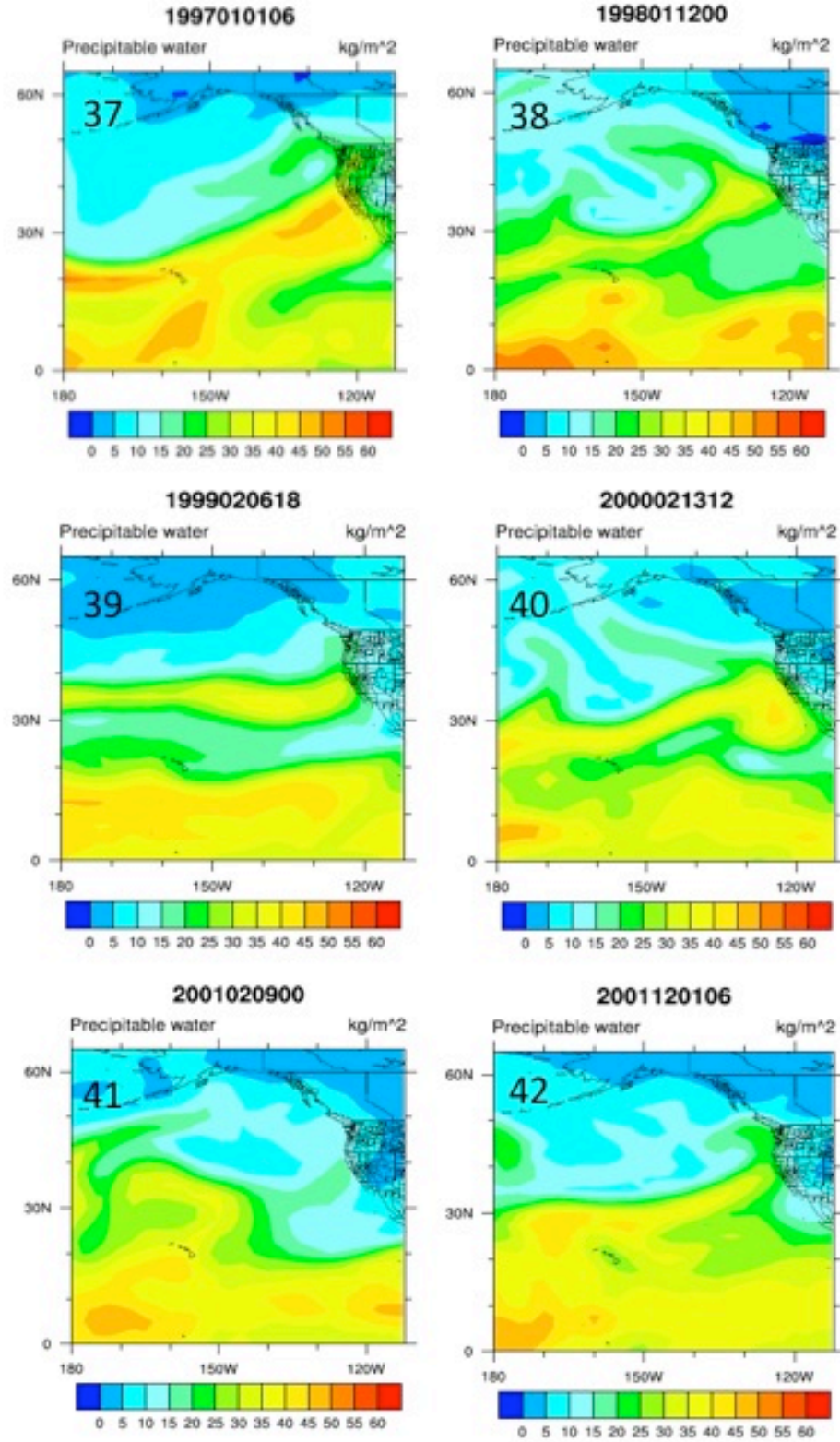


Figure 4.1 Pineapple express events that caused extreme precipitation and flood (continued)

For further investigation of the relation of pineapple express and the extreme precipitation events that caused flooding, 6 hourly precipitable water analyses between 1950 and 2002 from October to February were performed in order to show whether there were some pineapple express events that have not caused any flood. The results are shown in Figure 4.2 where four historical pineapple express events that did not cause flooding, were identified. Hence it is concluded that during the historical observation period (1950-2002), there are pineapple express related weather systems that do not render any extreme precipitation caused flood event at the American River Watershed although PE is localized on the ARW. There are many possible reasons for this. One of which is that soil may not be saturated enough, therefore the duration of PE over the watershed becomes important. The other reason may be related to the wind field which makes the direction of PE vary rapidly that PE may not impact on the watershed not staying there long enough.

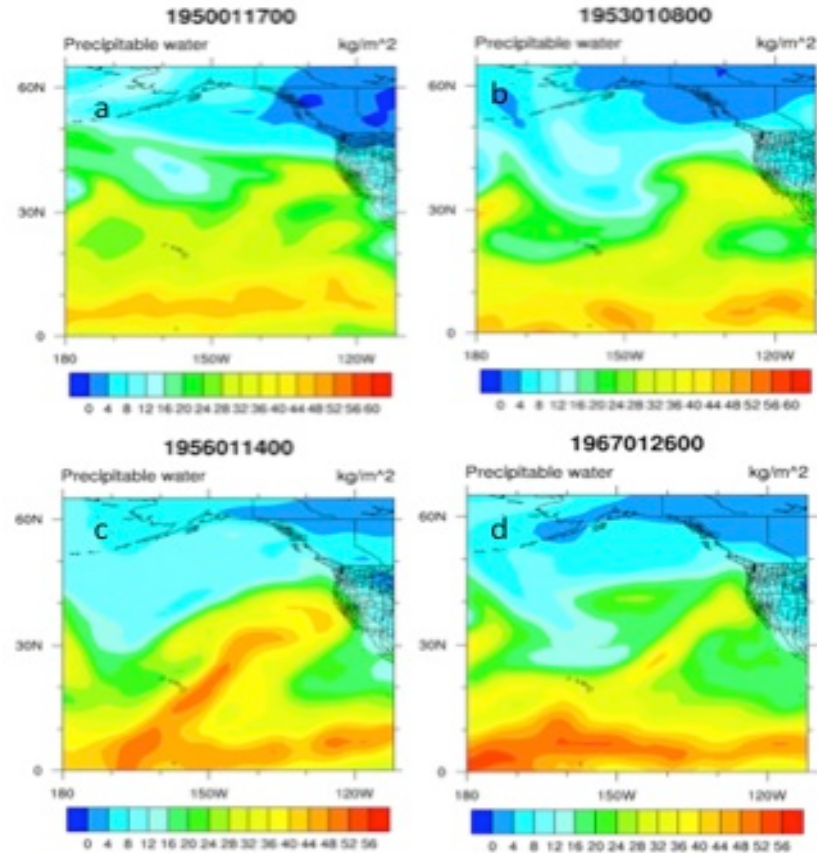


Figure 4.2 Pineapple express events that did not cause extreme precipitation and flood

Therefore, it may be inferred that not all of the pineapple express occurrences produce extreme precipitation events and floods at the ARW, although they might produce flood in a near location. In other words, the observations of the precipitable water imply that the occurrence of the pineapple express is necessary but it is not a sufficient condition for the production of maximum precipitation at the ARW. Thus, it is necessary to evaluate specific pineapple express mechanisms, such as direction, magnitude and duration of moisture inflows to California, in order to determine their importance in the production of maximum precipitation.

4.1.1 Direction, magnitude, and duration of the Pineapple Express

When precipitable water observations from 1950 to 2002 for the months of October, November, December, January and February were analyzed over California, it was hypothesized that maximum precipitation may be correlated to the direction, magnitude, and duration of the pineapple express phenomenon. In order to test this hypothesis, several pineapple express events that extended to the American river basin from different directions were investigated, as shown in Figure 4.3.

The January 1997 historical event was simulated altering its actual initial and boundary mixing ratio conditions with mixing ratios of the selected pineapple express events, demonstrated in Figure 4.3, in order to assess the pineapple express effect only. Maximum 72-hr basin-averaged precipitation estimates, obtained from these analyses, are presented in the lower-right corner of the Figure 4.3. Recalling from Table 3.2, the maximum observed precipitation of the 1997 case is 11.48 inches (Figure 4.3.i). Figure 4.3 also shows that precipitation is highly sensitive to mixing ratio, which is driven by the direction, magnitude, and duration of the pineapple express (PE).

Figure 4.3.c implies the importance of the direction of PE since its shift to North in this case brings no precipitation to the American River Watershed (ARW). The PE duration also plays an important role, since with longer PE durations the high mixing ratio can stay longer over the basin (not shown here). It can be clearly seen from Figure 4.3 that high precipitation is obtained due to high mixing ratio, which needs to be transported to the ARW from the coastal region of California. Although the PE moisture content is high in magnitude, it needs to be advected to the California inland to render substantial precipitation. Therefore, besides the moisture amount, wind may also be a significant factor in the determination of

maximum precipitation, since it brings moisture to the ARW. Consequently, the pineapple express observations are consistent with the relation that moisture flux convergence is proportional to the precipitation amount, which will be derived in the next section.

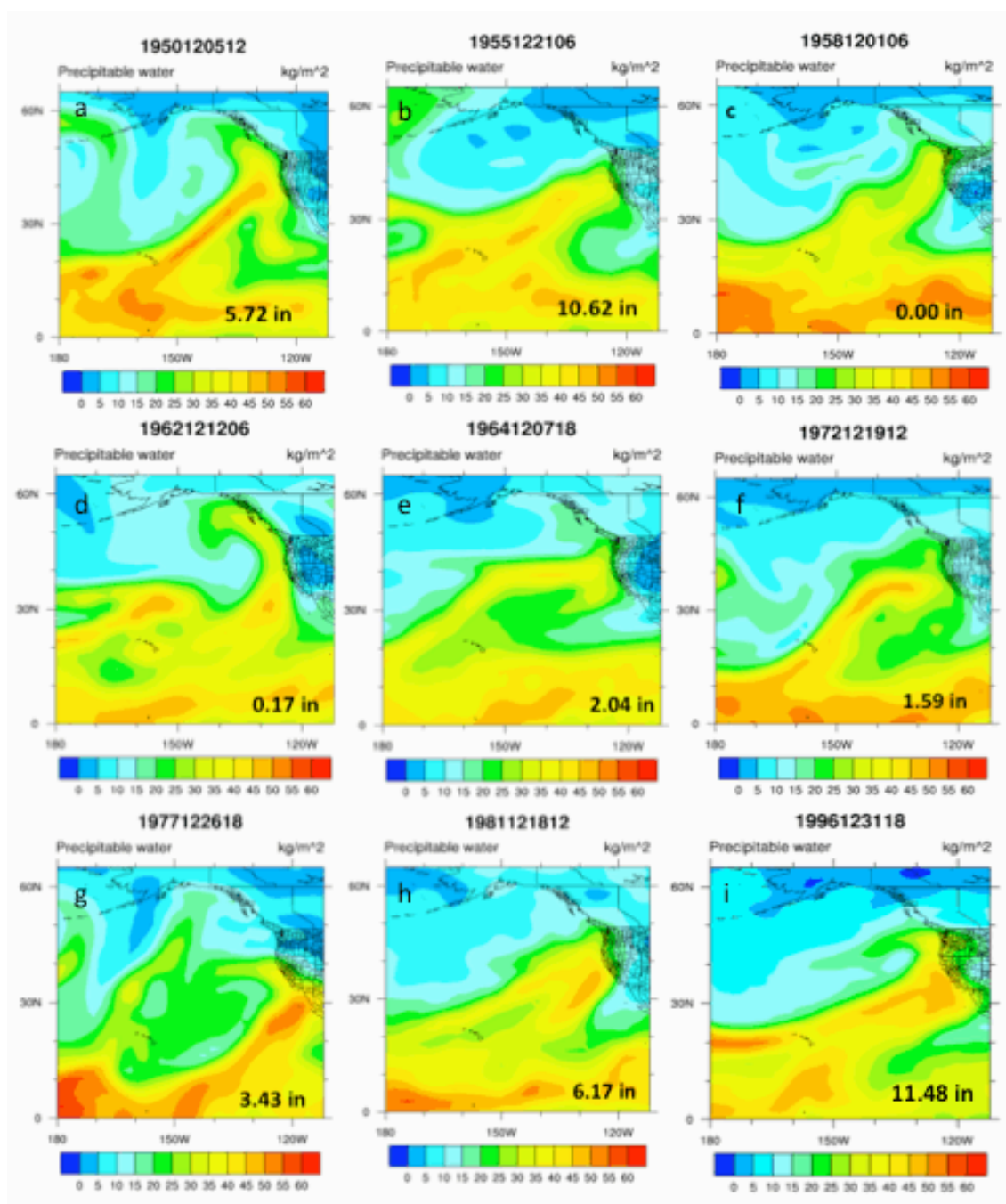


Figure 4.3 Pineapple express effect on maximum precipitation of January 97

4.2 Moisture Flux Convergence (MFC)

4.2.1 Theory of MFC

In this subsection, the equations by *Banacos and Schultz* (2005) are followed. Conservation of water vapor in pressure coordinates is expressed as,

$$\frac{dq}{dt} = S \quad (4.1)$$

where q is specific humidity and S represents the change in storage of water vapor. Storage of water vapor, S , is the difference between the source and sinks of water vapor following an air parcel. Generally, source terms are described by evaporation rate into the air parcel, E , whereas sink terms are represented by condensation rate in the air parcel, C . As a common practice [*Palmen and Holopainen*, 1961; *Banacos and Schultz* 2005], it is assumed that all the condensed water precipitates immediately out, denoted by P , so that

$$S = E - P \quad (4.2)$$

The left hand side of Equation 4.1, the total derivative of specific humidity, can be expanded in vector notation as,

$$\frac{dq}{dt} = \frac{\partial q}{\partial t} + \mathbf{V} \cdot \nabla q \quad (4.3)$$

where $\mathbf{V} = (u; v; \omega)$. Equation 4.3 can also be written in scalar notation as,

$$\frac{dq}{dt} = \frac{\partial q}{\partial t} + u \frac{\partial q}{\partial x} + v \frac{\partial q}{\partial y} + \omega \frac{\partial q}{\partial p} \quad (4.4)$$

Continuity equation for incompressible flow can be written in vector notation as

$$\nabla \cdot \mathbf{V} = 0 \quad (4.5)$$

and its scalar notation in pressure coordinates is written as,

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial \omega}{\partial p} = 0 \quad (4.6)$$

Since equation 4.6 is a zero term, it can be multiplied by q and it can be added to both sides of equation 4.4, and an additional substitution of equations 4.1 and 4.2 into equation 4.4 yields,

$$\frac{\partial q}{\partial t} + u \frac{\partial q}{\partial x} + v \frac{\partial q}{\partial y} + \omega \frac{\partial q}{\partial p} + q \left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial \omega}{\partial p} \right) = E - P \quad (4.7)$$

Horizontal moisture flux convergence term can be written from equation 4.7 as,

$$-\nabla \cdot \mathbf{V}_h q = \underbrace{-u \frac{\partial q}{\partial x} - v \frac{\partial q}{\partial y}}_{\text{advection}} - \underbrace{q \left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \right)}_{\text{convergence}} \quad (4.8)$$

Equation 4.8 is written in vector notation as,

$$-\nabla \cdot \mathbf{V}_h q = -\mathbf{V}_h \cdot \nabla q - q \nabla \cdot \mathbf{V}_h \quad (4.9)$$

where $\nabla = \frac{\partial}{\partial x} \mathbf{i} + \frac{\partial}{\partial y} \mathbf{j}$ and $\mathbf{V}_h = (u; v)$.

Similarly, vertical moisture flux term can be written from equation 4.7 as,

$$-\frac{\partial}{\partial p}(\omega q) = -\omega \frac{\partial q}{\partial p} - q \frac{\partial \omega}{\partial p} \quad (4.10)$$

Therefore, equation 4.7 becomes in vector notation as,

$$\underbrace{\frac{\partial q}{\partial t}}_{\text{local rate of change of } q} + \underbrace{\nabla \cdot \mathbf{V}_h q}_{\text{horizontal MFC}} + \underbrace{\frac{\partial}{\partial p}(\omega q)}_{\text{vertical MFC}} = \underbrace{E - P}_{\text{sources and sinks}} \quad (4.11)$$

A solution of equation 4.11 for P-E at the surface, vertically integrated over the depth of the atmosphere from the surface $p = p_s$ to $p = 0$ yields,

$$P - E = -\frac{1}{g} \int_0^{p_s} \frac{\partial q}{\partial t} dp - \frac{1}{g} \int_0^{p_s} \mathbf{V}_h \cdot \nabla q dp - \frac{1}{g} \int_0^{p_s} q \nabla \cdot \mathbf{V}_h dp \quad (4.12)$$

Vertical integration of vertical MFC over the depth of the atmosphere is zero.

Palmen and Holopainen [1961] suggested that precipitation intensity in equation (4.12) should be replaced by its mean over a limited period of time, so that satisfactory agreement

between observation and computed precipitation can be obtained. Therefore equation 4.12 is averaged into the form

$$\bar{P} - \bar{E} = \underbrace{-\frac{1}{g} \int_0^{p_s} \overline{\frac{\partial q}{\partial t}} dp}_{\text{Term I}} - \underbrace{\frac{1}{g} \int_0^{p_s} \overline{\mathbf{V}_h \cdot \nabla q} dp}_{\text{Term II}} - \underbrace{\frac{1}{g} \int_0^{p_s} \overline{q \nabla \cdot \mathbf{V}_h} dp}_{\text{Term III}} \quad (4.13)$$

In cases of no divergence in the atmospheric column or lower divergence and upper convergence (Term III in equation 4.13), which yields descending motion, P either vanishes or becomes negligible. Therefore E is approximated by the sum of Term I and Term II in equation 4.13.

As a result, in the above, since E in a cyclonic situation with heavy precipitation must be small compared to P, it is expected that Term I and Term II in equation 4.13 should be small compared to Term III in the same equation. Thus, the rate of precipitation may be taken proportional to the vertically integrated product of mixing ratio and mass convergence through the depth of the atmosphere:

$$\bar{P} \approx -\frac{1}{g} \int_0^{p_s} \overline{q \nabla \cdot \mathbf{V}_h} dp \quad (4.14)$$

4.2.2 Modeling of MFC

As was discussed in Chapter II, the WRF model solves conservation equations of the hydrometeor species with recalling equation (2.9):

$$\partial_t Q_m + (\nabla \cdot \mathbf{V} q_m) = F_{Q_m} \quad (4.15)$$

where $Q_m = \mu_d q_m$, F_{Q_m} is the forcing term, $q_m = q_v, q_c, q_r, q_i, q_g, q_s$ and are mixing ratios of water vapor, cloud vapor, rain, ice, graupel, and snow, respectively.

Table 4.1 The WRF model precipitation versus convergence term of MFC correlations

Water Year	Correlation	Water Year	Correlation	Water Year	Correlation
1951	0.87	1975	0.60	1989	0.80
1956	0.84	1976	0.87	1990	0.51
1963I	0.89	1977	0.62	1991	0.71
1963II	0.82	1978	0.61	1992	0.56
1965	0.75	1979	0.88	1993	0.74
1966	0.87	1980	0.81	1994	0.51
1967	0.61	1981	0.70	1995	0.80
1968	0.91	1982	0.75	1996	0.85
1969	0.56	1983	0.62	1997	0.89
1970	0.80	1984	0.71	1998	0.74
1971	0.47	1985	0.47	1999	0.57
1972	0.48	1986	0.71	2000	0.63
1973	0.66	1987	0.75	2001	0.55
1974	0.87	1988	0.67	2002	0.68

Specific humidity, q , is the ratio of water vapor to air (including water vapor and dry air) in a particular mass; whereas mixing ratio, w , is the ratio of water vapor to dry air. The relationship between mixing ratio and specific humidity can be expressed as,

$$w = \frac{q}{1 - q} \quad (4.16)$$

Due to the fact that $q \ll 1$, mixing ratio and specific humidity are used interchangeably in practice. Hence, Equation 4.15 (or Equation 2.9) is identical to Equation 4.1, and the experiments, reported here, show that the rain-mixing ratio should be used in Equation 4.14 as an approximation for precipitation.

Correlation analyses were performed to show that Equation 4.14 is valid for pineapple express (PE) analyses. Convergence term of moisture flux convergence (MFC), defined by the right hand side of Equation 4.14 were computed first. Rain mixing ratio and velocity outputs of the WRF are interpolated to pressure coordinates from η coordinates in order to perform the vertical integration as a function of pressure. Then these precipitation approximations were correlated to the WRF model precipitation output over AR basin domain. 72-hr maximum vertical distributions of convergence term of horizontal MFC are presented in Figure 4.4 for the 42 historical extreme precipitation cases.

The correlations between precipitation and convergence term of moisture flux convergence are presented in Table 4.1. Their average correlation over the 42 historical events is 0.71. These results show that the pineapple express related precipitation is mostly due to MFC rather than local moisture changes. Therefore, the traditional PMP analyses are not realistic for the PMP estimates over AR basin since they do not consider MFC.

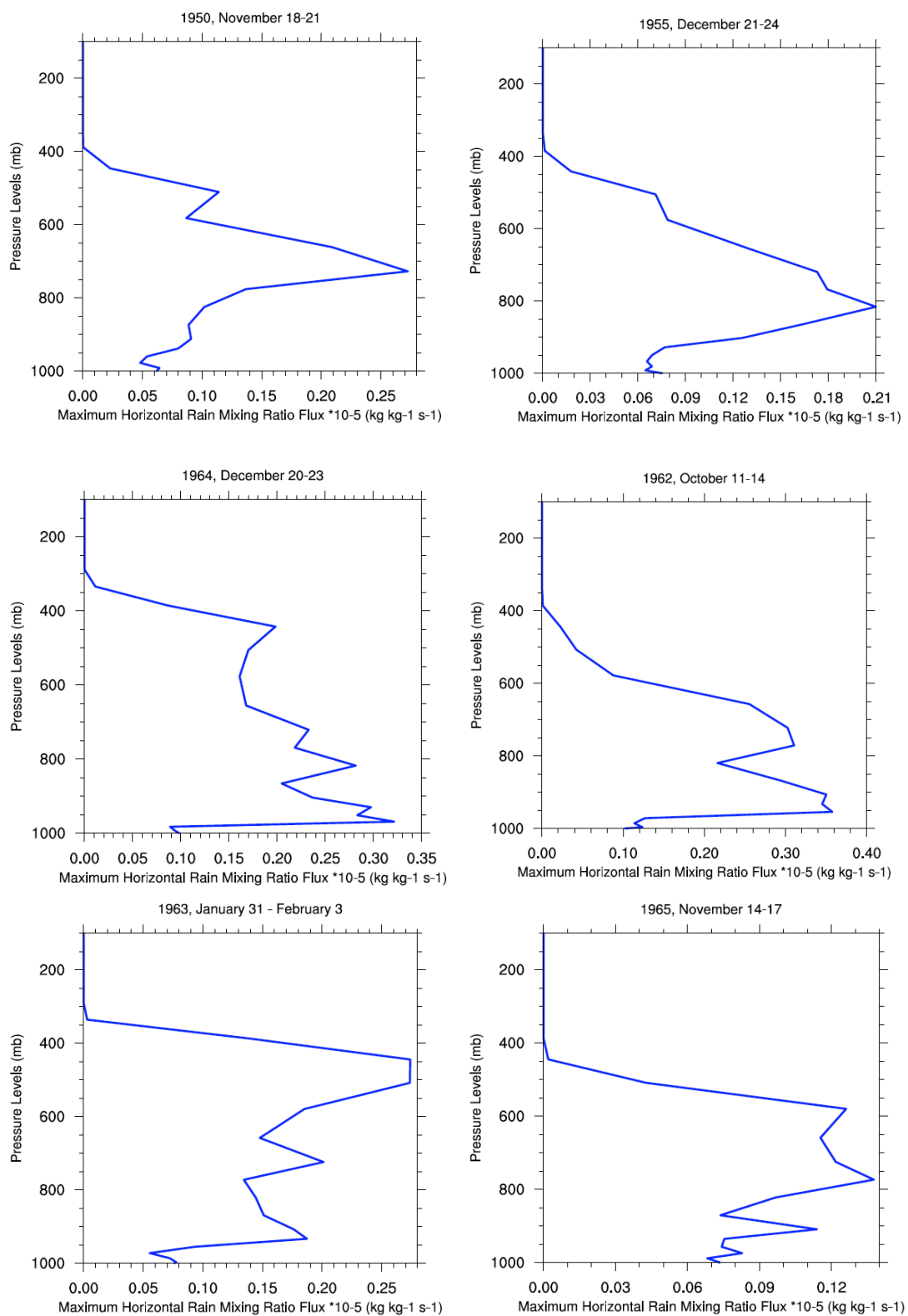


Figure 4.4 Horizontal moisture flux profiles for 42 historical cases

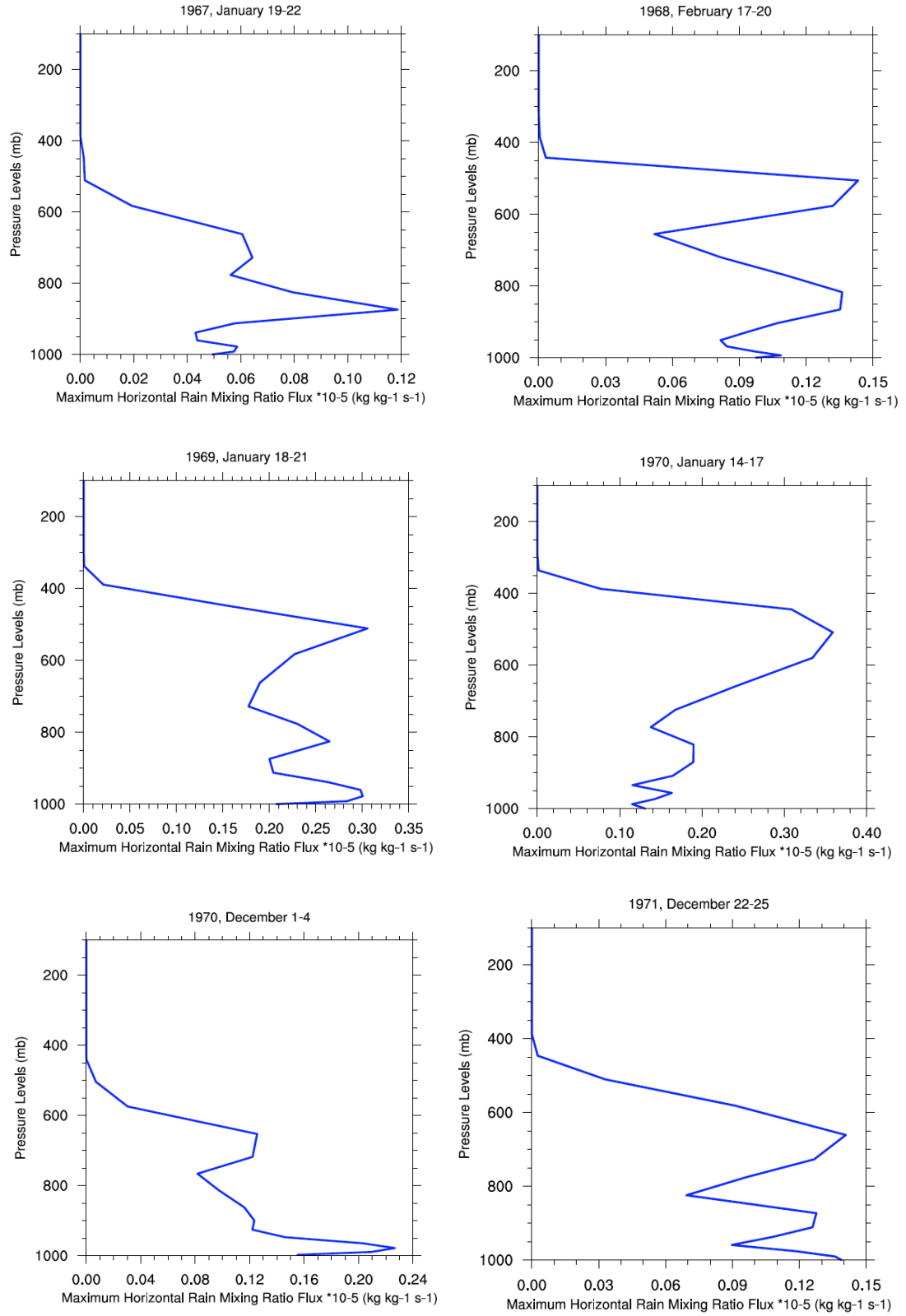


Figure 4.4 Horizontal moisture flux profiles for 42 historical cases- continued

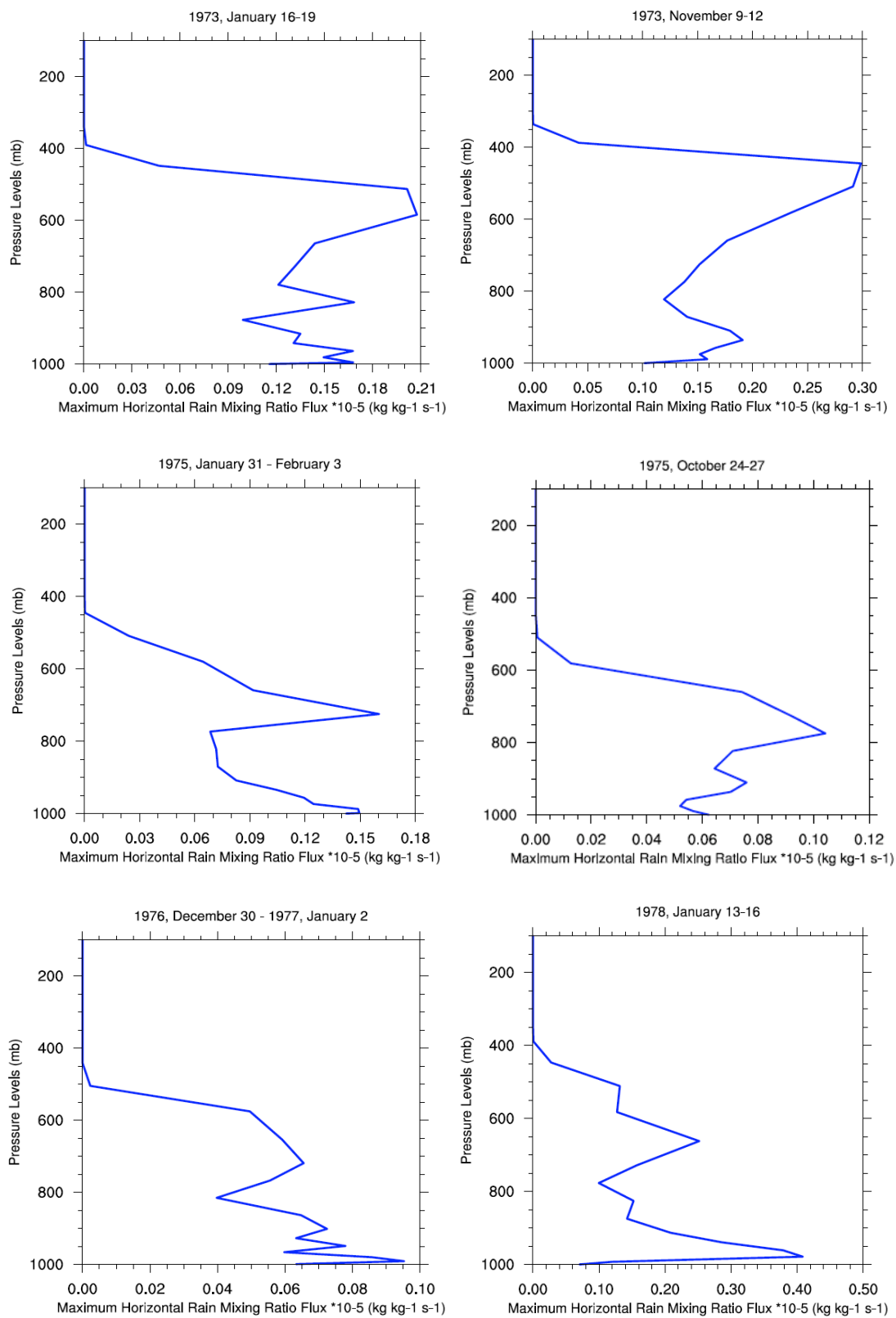


Figure 4.4 Horizontal moisture flux profiles for 42 historical cases- continued

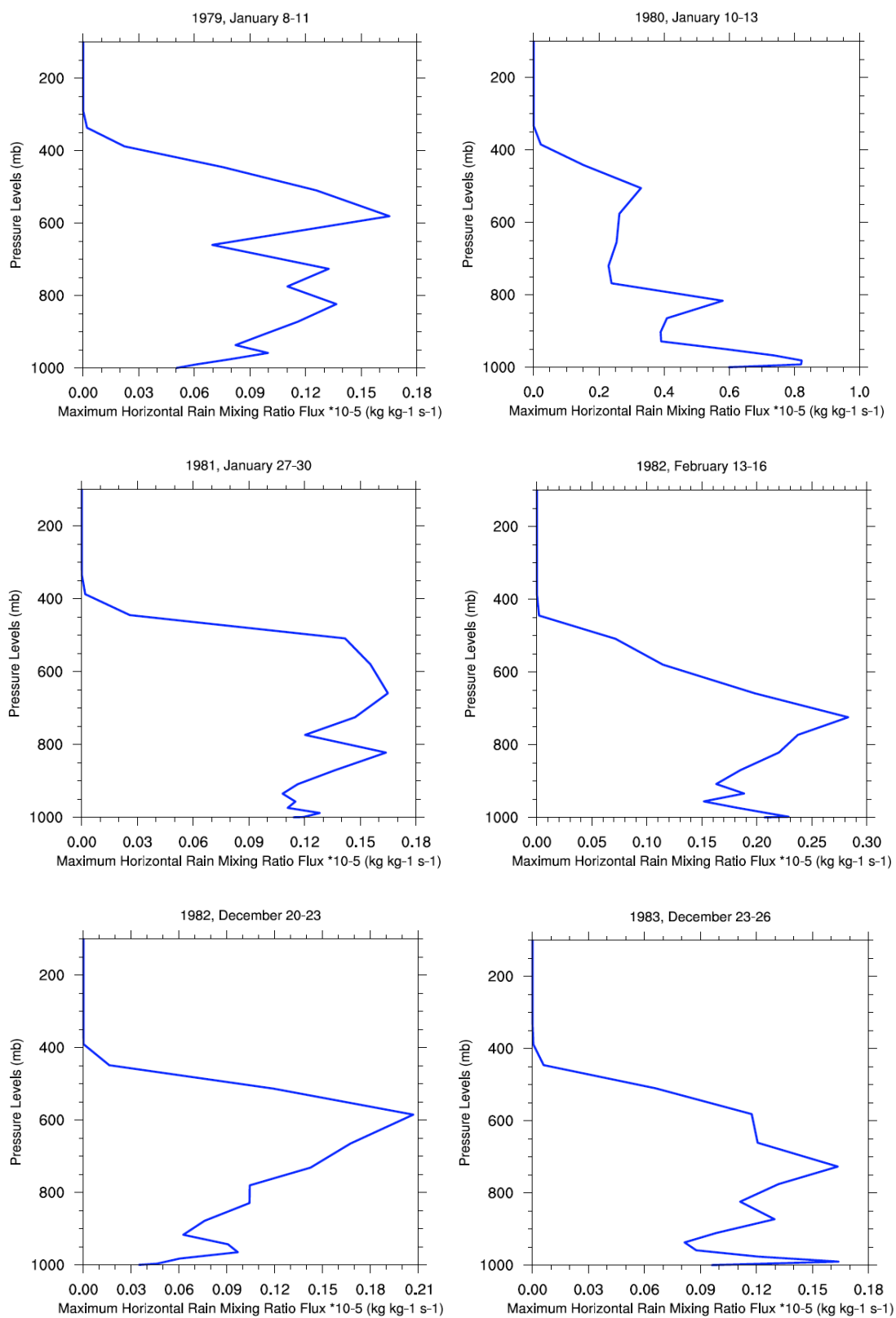


Figure 4.4 Horizontal moisture flux profiles for 42 historical cases- continued

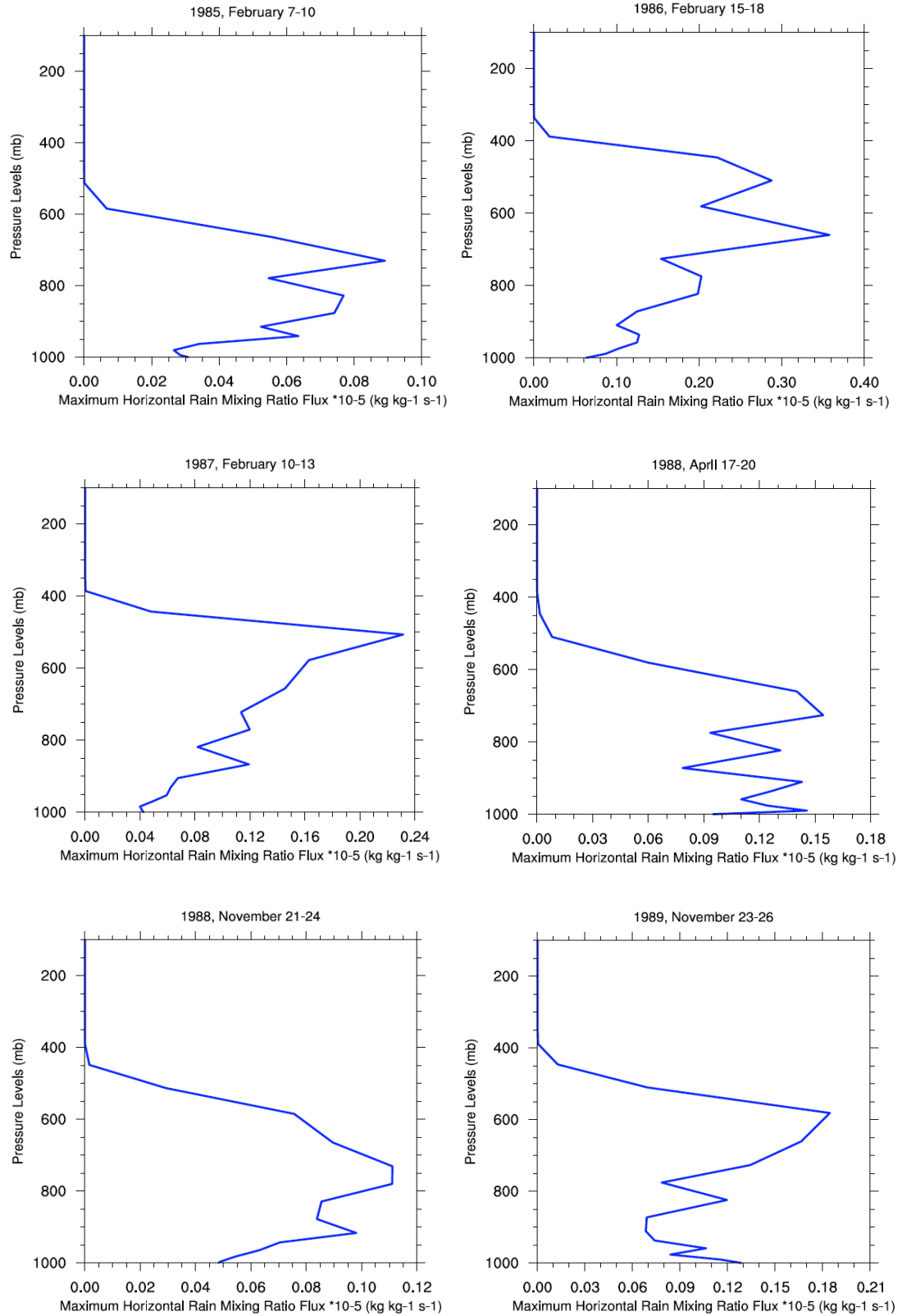


Figure 4.4 Horizontal moisture flux profiles for 42 historical cases- continued

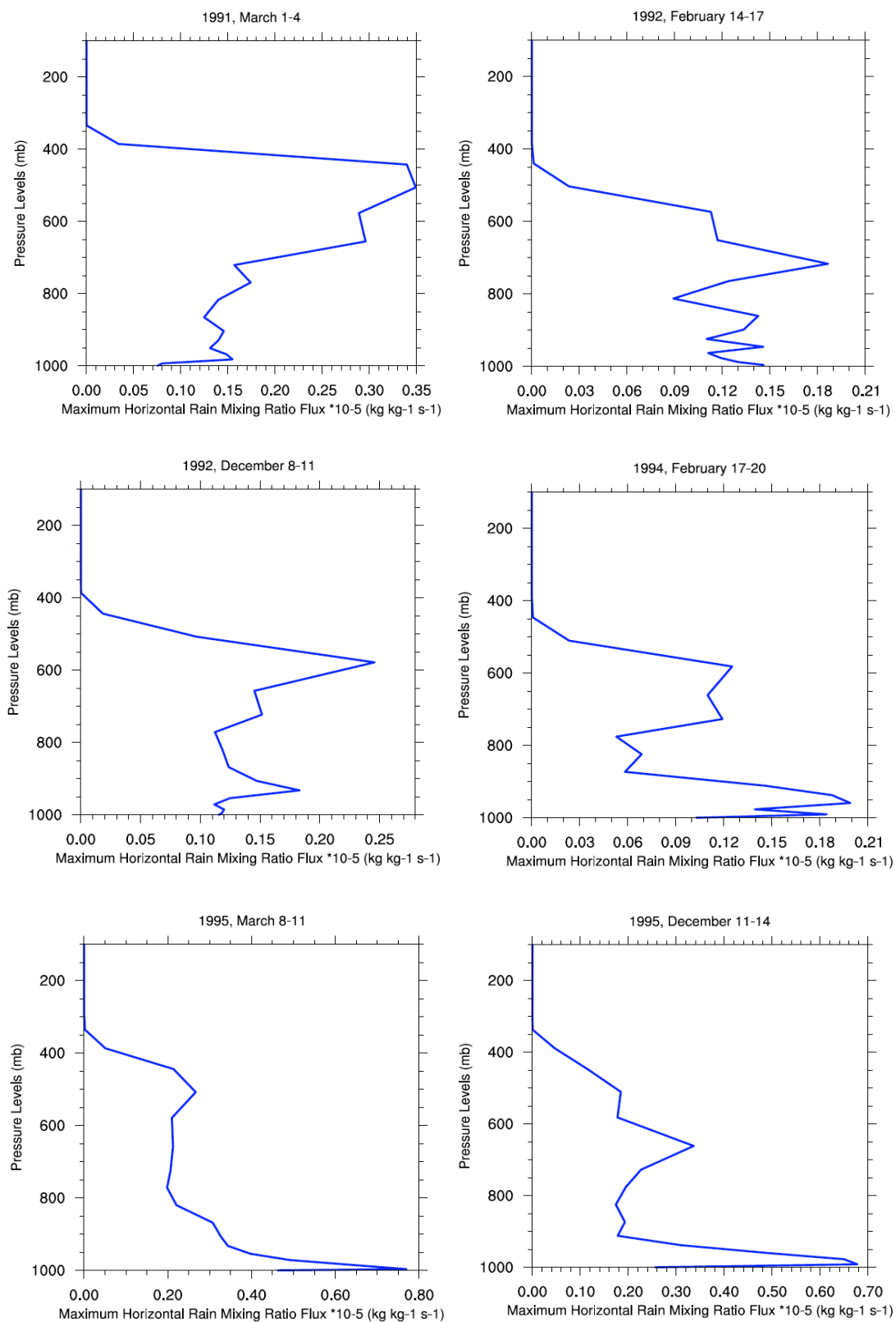


Figure 4.4 Horizontal moisture flux profiles for 42 historical cases- continued

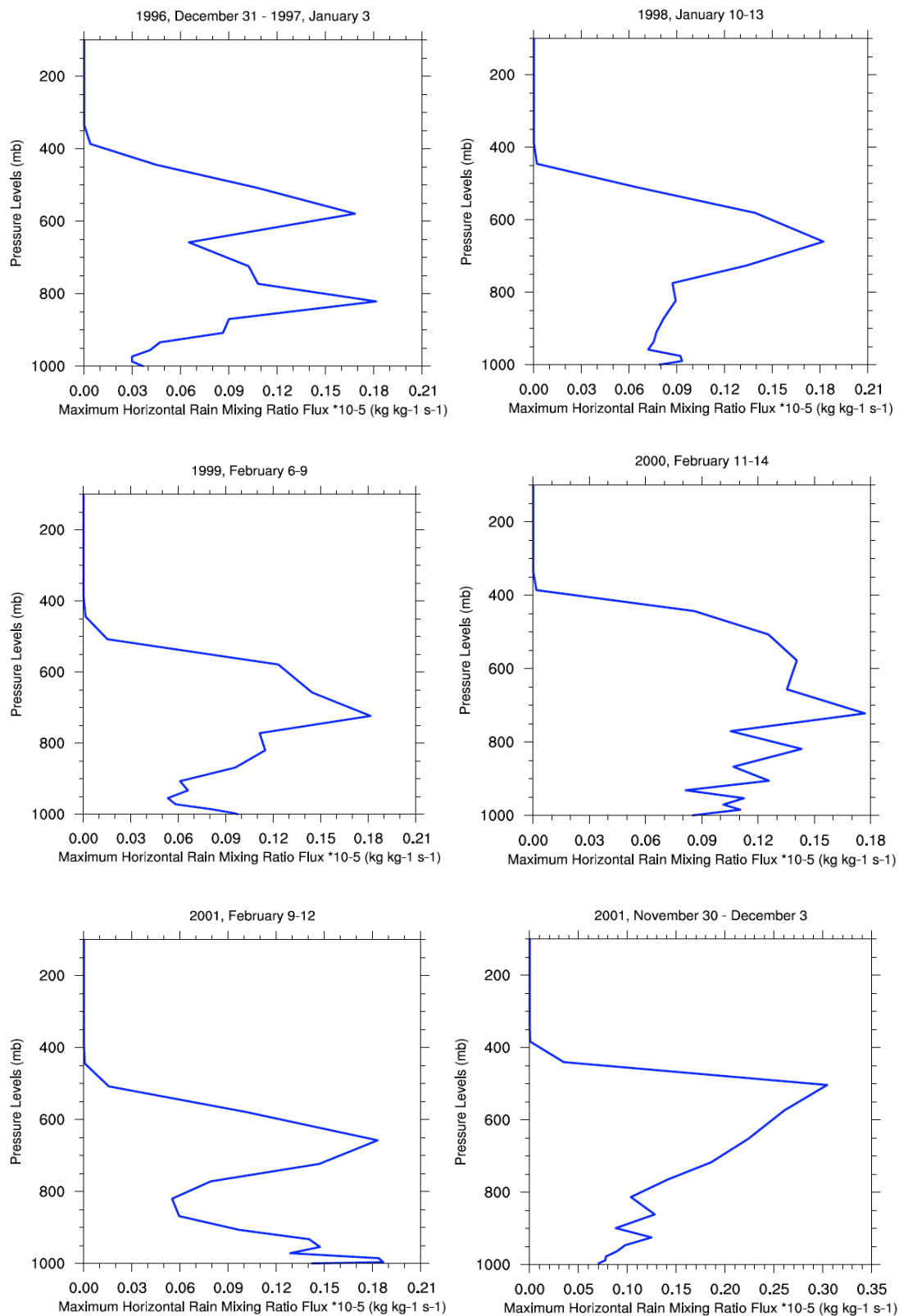


Figure 4.4 Horizontal Moisture Flux Profiles for 42 historical cases-continued

As one can see from Figure 4.4, the vertical distribution of convergence term of MFC has a chaotic behavior. MFC is not pronounced above the pressure levels between 300mb and 500mb based on 42 historical cases, since the mixing ratio decreases with height and reaches to zero in these levels, although wind is high. There is no distinct pressure level range for maximum MFC based on these historical cases. Moreover, it is seen from these figures that the maximum MFC can occur at more than one pressure level for each case. The maximum MFC range is between $0.09 \times 10^{-5} \text{ kg kg}^{-1} \text{ s}^{-1}$ to $0.78 \times 10^{-5} \text{ kg kg}^{-1} \text{ s}^{-1}$.

More importantly, Figure 4.4 shows that the low-level mixing ratio adjustment method [Chen, 2005] does not work for the American River Watershed, since this method considers the pressure levels below 850mb for the mixing ratio adjustment as a method for moisture maximization. However, according to Figure 4.4, there are levels higher than 850mb where moisture transport is more significant.

4.3 Precipitation Maximization Methods

All of the observational analyses and their simulations for the 42 historical extreme precipitation events during 52 years show that there is a close relationship between moisture and precipitation amount, similar to the results of *Abbs* [1999]. As was described in the previous sections, the maximum precipitation occurs due to the pineapple express phenomenon, which brings extensive amount of moisture to the AR basin. Available moisture over the basin is mainly dependent upon the moisture flux convergence (MFC), which is a function of advection and convergence of moisture. Therefore, in this section, some new techniques to maximize moisture flux convergence, in terms of the maximization

of moisture and wind fields, will be established. Mainly four different techniques will be performed in order to evaluate maximum precipitation: 1. Perturbations of atmospheric conditions; 2. Shift in atmospheric conditions; 3. Replacement of atmospheric conditions among historical events; and 4. Thermodynamically possible worst-case scenario creation.

4.3.1 Perturbations of Atmospheric Conditions

Here the initial and boundary conditions of the WRF model are perturbed in a physically possible way, so that one can determine a range for maximum precipitation. This type of experiment is performed in four stages. First, only the moisture field is perturbed. Then perturbations are performed only on the wind field. In the third stage, perturbations to both moisture and wind fields are applied in order to assess their combined effect. In the last stage, the effect of initial and boundary conditions are evaluated. Additionally, a similar test with respect to initial condition only is also performed.

4.3.1.1 Moisture Perturbation Effect

Based upon the above finding that moisture convergence into the AR Watershed is one of the key parameters, the relative humidity of the 42 historical flood events were analyzed, and their range over the ARW were determined. The results are shown in Table 4.2 below.

The relative humidity variations of 42 storms, presented in Table 4.2, were vertically integrated with respect to pressure using NCEP/NCAR data. Consistent with the general knowledge, the relative humidity ranges from 0% to 100% for the Eastern Pacific domain shown in Figure 4.1.

Table 4.2 Minimum and maximum values of relative humidity and wind velocity for 42 extreme precipitation events during a 52-year historical period

Max 72hr Storm period start-end (hourly)								RH (%)		u wind (m/s)		v wind (m/s)	
Water	Year	M	D	H	M	D	H	min	max	min	max	min	max
1951	1950	11	18	8	11	21	8	0.0	100.0	-36.7	75.6	-67.9	61.1
1956	1955	12	21	6	12	24	6	0.0	100.0	-36.3	81.3	-61.9	50.3
1963I	1962	10	11	8	10	14	8	0.0	100.0	-46.3	87.3	-71.8	69.0
1963II	1963	1	31	6	2	3	6	0.0	100.0	-49.6	103.2	-60.3	63.2
1965	1964	12	20	13	12	23	13	0.0	100.0	-52.8	87.8	-85.2	57.3
1966	1965	11	14	9	11	17	9	0.0	100.0	-44.0	81.6	-68.2	61.2
1967	1967	1	19	11	1	22	11	0.0	100.0	-60.3	104.4	-90.3	63.7
1968	1968	2	17	7	2	20	7	0.0	100.0	-52.9	96.5	-55.2	58.2
1969	1969	1	18	21	1	21	21	0.0	100.0	-40.3	91.5	-64.7	66.3
1970	1970	1	14	0	1	17	0	0.0	100.0	-58.6	98.9	-56.8	55.9
1971	1970	12	1	10	12	4	10	0.0	100.0	-36.2	88.4	-73.5	66.5
1972	1971	12	22	20	12	25	20	0.0	100.0	-49.5	85.1	-75.7	67.4
1973	1973	1	16	4	1	19	4	0.0	100.0	-51.3	92.7	-79.6	64.4
1974	1973	11	9	18	11	12	18	0.0	100.0	-46.8	83.5	-76.0	62.9
1975	1975	1	31	13	2	3	13	0.0	100.0	-43.3	103.9	-65.0	62.2
1976	1975	10	24	19	10	27	19	0.0	100.0	-34.4	84.3	-67.3	57.3
1977	1976	12	30	23	1	2	23	0.0	100.0	-52.5	101.2	-69.7	71.7
1978	1978	1	13	21	1	16	21	0.0	100.0	-38.9	100.4	-92.2	61.3
1979	1979	1	8	21	1	11	21	0.0	100.0	-62.2	93.6	-83.9	58.9
1980	1980	1	10	23	1	13	23	0.0	100.0	-47.7	106.0	-120.9	70.6
1981	1981	1	27	4	1	30	4	0.0	100.0	-52.2	103.0	-62.9	64.9
1982	1982	2	13	13	2	16	13	0.0	100.0	-46.0	97.5	-73.1	62.1
1983	1982	12	20	14	12	23	14	0.0	100.0	-48.4	95.4	-82.6	68.4
1984	1983	12	23	6	12	26	6	0.0	100.0	-55.0	92.8	-91.6	68.7
1985	1985	2	7	3	2	10	3	0.0	100.0	-35.3	80.9	-74.6	70.6
1986	1986	2	15	9	2	18	9	0.0	100.0	-45.4	100.3	-97.3	71.0
1987	1987	2	10	19	2	13	19	0.0	100.0	-49.8	102.6	-83.2	65.9
1988	1988	4	17	10	4	20	10	0.0	100.0	-40.4	89.6	-72.4	56.4
1989	1988	11	21	15	11	24	15	0.0	100.0	-46.2	91.6	-73.6	65.1
1990	1989	11	23	19	11	26	19	0.0	100.0	-36.5	84.9	-72.6	71.0
1991	1991	3	1	14	3	4	14	0.0	100.0	-43.0	93.9	-69.9	64.5
1992	1992	2	14	9	2	17	9	0.0	100.0	-35.7	96.8	-71.2	58.9
1993	1992	12	8	19	12	11	19	0.0	100.0	-50.4	88.4	-69.2	65.3
1994	1994	2	17	0	2	20	0	0.0	100.0	-52.6	93.4	-85.6	61.8
1995	1995	3	8	17	3	11	17	0.0	100.0	-49.0	97.5	-69.5	56.6
1996	1995	12	11	1	12	14	1	0.0	100.0	-42.1	101.1	-70.1	76.6
1997	1996	12	31	6	1	3	6	0.0	100.0	-54.4	99.3	-83.2	66.2
1998	1998	1	10	0	1	13	0	0.0	100.0	-48.5	105.7	-78.5	56.7
1999	1999	2	6	14	2	9	14	0.0	100.0	-40.7	103.9	-64.9	61.5
2000	2000	2	11	16	2	14	16	0.0	100.0	-53.5	94.3	-79.3	66.0
2001	2001	2	9	6	2	12	6	0.0	100.0	-45.3	93.2	-72.0	59.6
2002	2001	11	30	8	12	3	8	0.0	100.0	-42.0	105.5	-70.9	72.6

For the 1997 event only, four perturbation simulations were performed to show how precipitation varies with only in the change in relative humidity. The relative humidity was changed from -30% to +30% for the whole atmospheric column at each model grid point, keeping all other variables the same as in the historical observations. For 30% increase case, when 100% limit is exceeded at some grid points, relative humidity is set to 100% for those grid points. According to Figure 4.5, the obtained results are consistent with those of *Zhao et al.* [1997], *Abbs* [1999], *Chen and Bradley* [2006], and *Chen and Bradley* [2007] that precipitation increases with relative humidity nonlinearly. 30% increment in relative humidity gives 14.31 inches basin average 72-hr maximum precipitation, which is 1.35 inches higher than the actual modeled amount under the 1997 event only. The values of Figure 4.5 are presented in 5-8th rows of Table 4.3.

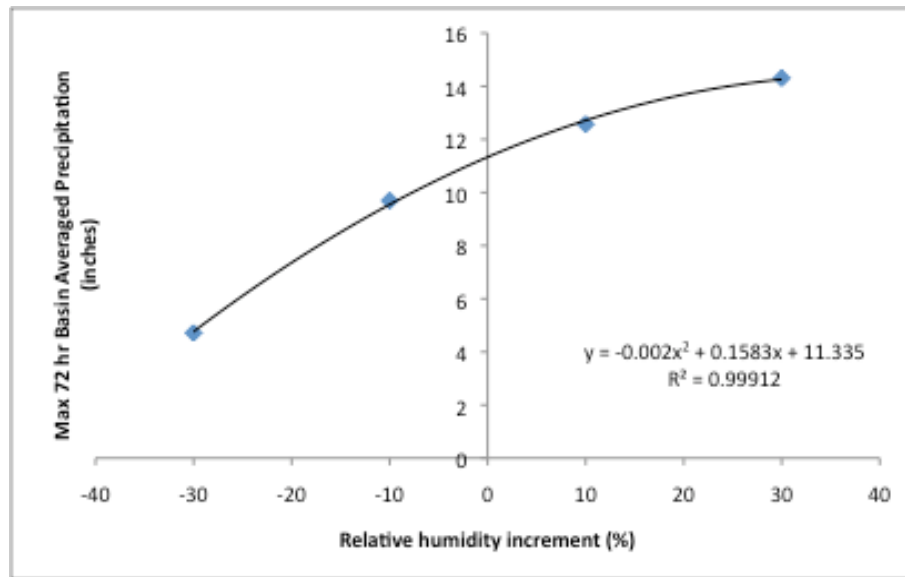


Figure 4.5 Maximum precipitation change with moisture only for the 1997 case

4.3.1.2 Wind Perturbation Effect

The wind perturbation effect which is the other significant term in determining moisture flux convergence, was evaluated in this study by setting initial and boundary conditions of the 1997 case from -10 m/s to +10 m/s in u and v components of the wind velocities for the whole column of the atmosphere. Although 10 m/s increment is arbitrarily chosen, it can be seen in Table 4.2, where the maximum and minimum wind speed is tabulated for 42 historical events, that 5 m/s to 20 m/s increment in wind velocities can be assumed reasonable. Moreover, wind perturbation method needs more attention, since the upper limit of wind speed can be exceeded easily and the simulation results, therefore, would be misleading.

As expected, the results in Figure 4.5 show that increasing the wind speed induces more moisture to the basin, causing exponentially increased precipitation.

Similarly, while keeping the same amount of moisture in the system, when the wind speed is decreased, the precipitation decreases due to less moisture convergence to the basin. As it is expected from the advection and convergence in Equation 4.8, there is a nonlinear relationship between the wind and the moisture flux, similar to the nonlinear relationship between the precipitation amount and the moisture flux.

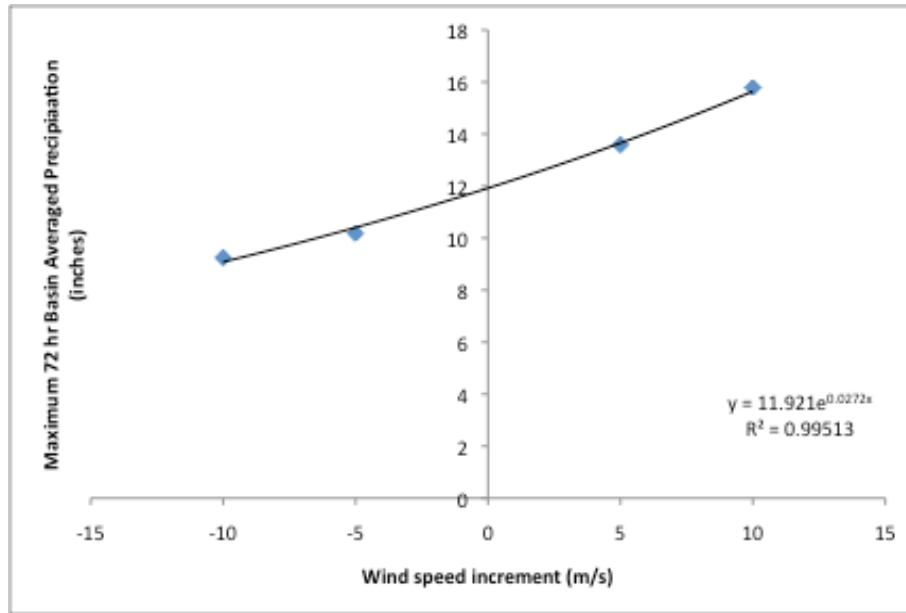


Figure 4.6 Maximum precipitation change with wind speed only for the 1997 case

As can be seen from Fig. 4.6, the 10 m/s increment in u and v components of the wind gives 15.79 inches 72-hr basin-average maximum precipitation which is 3.33 inches higher than the modeled amount for the 1997 historical flood case, and 1.48 inches higher than the amount of the maximum precipitation obtained by 30% increase in relative humidity. The values of Figure 4.5 are presented in 9-12th rows of Table 4.3.

4.3.1.3 Combined Moisture and Wind Perturbation Effect

Above it was shown that precipitation could be maximized by changing the relative humidity and the u , v components of the wind, individually. In order to evaluate how precipitation varies when both moisture and wind change, and the interactions of these two effects, a numerical simulation experiment, composed of 4 possible combinations, as proposed in the first four rows of Table 4.3, was performed.

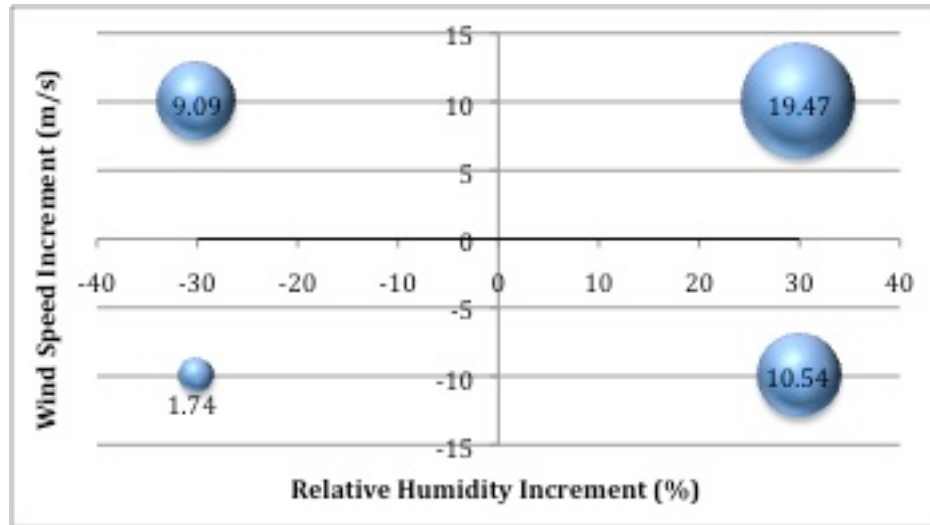


Figure 4.7 Combined moisture and wind perturbation effect on precipitation for the 1997 case

	RH (%)	U; V (m/s)	Max Precipitation (in)
1	+30	+10	19.47
2	-30	-10	1.74
3	+30	-10	10.53
4	-30	+10	9.08
5	+30	NO	14.31
6	+10	NO	12.57
7	-10	NO	9.69
8	-30	NO	4.71
9	NO	+10	15.79
10	NO	+5	13.59
11	NO	-5	10.18
12	NO	-10	9.25

Similar to above procedures, all atmospheric conditions were kept the same as in the historical case study of 1997. 19.47 inches of maximum precipitation is rendered varying only the relative humidity and the u, v components of the wind in the WRF model. This result amounts to a 7.01 inches increase in basin-averaged 72-hr maximum precipitation.

Meanwhile, the relative humidity-wind speed combinations, shown in Table 4.3, produce an additional result that (+30;-10) combination of RH and wind, respectively, is close to but not identical to the (-30;+10) pair. Before reaching a conclusion, this result needs to be analyzed further, yet it is out of the scope of this research at this time.

4.3.1.4 Perturbations in Initial and Boundary Conditions

In this section, the aim is to investigate the variation in precipitation over the ARW due to the changes in the initial and boundary conditions. For this purpose, the analyses of the wind perturbation effect section are evaluated further. The model is set as shown in Table 4.4 where only the u and v component of wind was perturbed from 10 m/s to 20 m/s with a 5 m/s interval. This case was simulated under two conditions: 1. Only the perturbation in the initial conditions was considered (IC only section in Table 4.4.); 2. Perturbations were considered both in the initial and boundary conditions (IC+BC section in Table 4.4).

Table 4.4 IC only and combined IC+BC effects on precipitation based on wind maximization (1997 event only)		
IC/BC	u;v (m/s)	MP (in)
IC only	+10	11.64
IC only	+15	11.73
IC only	+20	11.49
IC+BC	+10	15.79
IC+BC	+15	18.42
IC+BC	+20	20.06

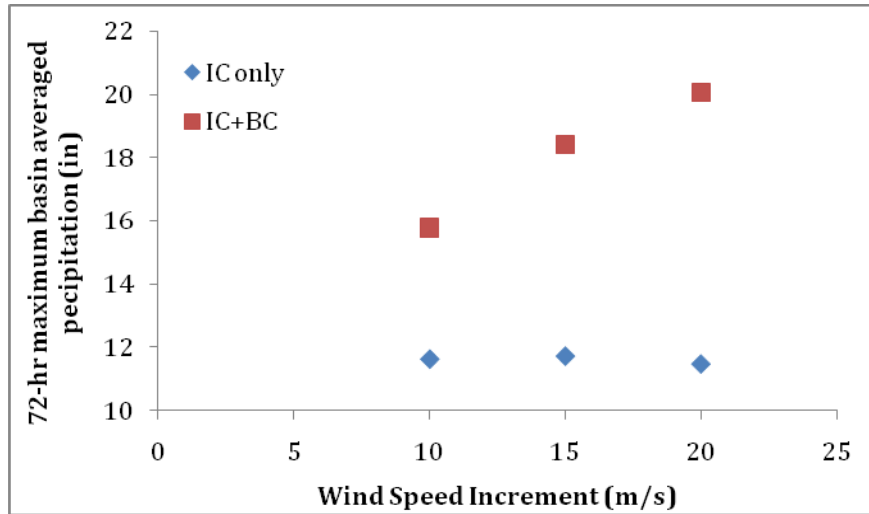


Figure 4.8 IC only and combined IC+BC effects on precipitation for the 1997 case only

The model results of the 72-hr maximum basin averaged maximum precipitation are presented in Table 4.4 and their illustration is given in Figure 4.8. The maximum precipitation that is obtained from 10 m/s increment in u and v component of wind under both initial condition (IC) and boundary condition (BC) change is 15.79 inches, being similar to the obtained amount under the wind perturbation effect (9th row of Table 4.3). On the other hand, 11.64 inches maximum precipitation is simulated when only the initial condition of wind speeds is increased 10 m/s, as shown in Table 4.4 and Figure 4.8. This amount is very close to the originally modeled one, which is 11.48 inches. Moreover, there is a conflict that the maximum precipitation amount is not increased by wind speed when only the initial conditions are changed. Similar to the findings in the wind perturbation section, the maximum precipitation increases with wind speed when both initial and boundary conditions change (Figure 4.8).

These results show that perturbations should be applied to both initial and boundary conditions in order to obtain reasonable results for maximum precipitation. The result obtained from perturbations in initial conditions only may be misleading.

Based on the results shown in Table 4.3 and Table 4.4, this experiment has another consequence that the initial and boundary condition perturbations in wind speeds only by +20 m/s might be equivalent to the IC/BC perturbations in both relative humidity by 30% and wind speed by +10m/s.

As a result, although the approach of perturbations of atmospheric conditions may help to obtain maximum precipitation, it is difficult to determine how much perturbation would yield physically possible maximum precipitation due to the chaotic behavior of the system. Therefore, this method shall not be used to determine the physically possible PMP over AR Watershed.

4.3.2 Replacement of atmospheric conditions with respect to land conditions

A third possible maximization avenue is the exchange of the historical atmospheric conditions among the historical events in order to investigate whether any different atmosphere-land interaction, corresponding to a historical case, can cause higher precipitation than the historical precipitation which actually occurred. Five high-ranked flood events were chosen for this experiment, and the atmospheric conditions of each event were replaced by the atmospheric conditions of other events. Then these new conditions were simulated. For instance, the atmospheric conditions of the 1997 event were combined with the land conditions of 1965, 1986, 1963I, and 1956 events to see if higher precipitation amounts could be obtained by means of these combinations.

atm\land	1956	1963I	1965	1986	1997
1956 atm	13.078	13.747	13.044	13.188	13.178
1963I atm	12.798	13.781	12.759	13.909	12.719
1965 atm	15.212	16.102	14.999	15.685	15.252
1986 atm	12.543	13.704	12.449	12.538	12.631
1997 atm	11.492	12.124	11.469	11.859	11.484

The WRF model results for these replaced events are presented in Table 4.5, and they are summarized in Figure 4.9. The abscissa of Figure 4.9 denotes the years that land conditions are fixed. Each year of land in the abscissa has five clustered years for the atmospheric conditions, which are represented by colored bars. The ordinate shows the maximum precipitation amounts for the American River Basin. For example, yellow bars denote the atmospheric conditions for 1965. Therefore, the yellow bar, placed in the cluster of 1965 of the abscissa, represents the actual atmosphere-land conditions.

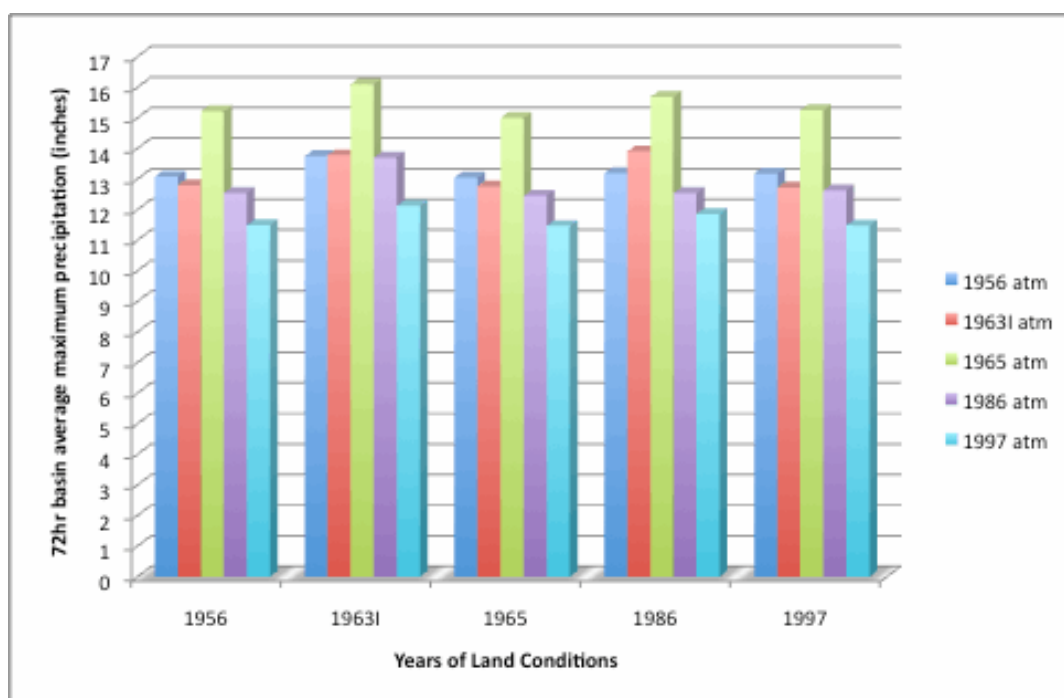


Figure 4.9 The WRF precipitation results of replaced events

The results show the effect of the land conditions on precipitation. They show that a combination of the appropriate atmosphere-land coupling can cause an increase in precipitation by around one inch. Since there are two 1963 water year event in 42 historical events, these two events are named by 1963I and 1963II as shown in Table 3.2. A combination of the land conditions of 1963I and the atmospheric conditions of 1986

causes 1.166 inches increase in the maximum precipitation of 1986. On the other hand, the highest modeled maximum precipitation, which has occurred in 1965 with 14.999 inches, increases to 16.102 inches by replacing the original 1964 land conditions by the land conditions of 1963I. For further conclusions, atmosphere land interactions for the American River Watershed need to be evaluated in detail for all 42 storms. However, such an effort would be a costly research effort.

4.3.3 Shift in atmospheric conditions

It is seen from the observations (Figures 4.1, 4.2, and 4.3) that the pineapple express events may not hit the studied basin exactly, even though the high-ranked maximum precipitation may occur over the basin. For instance, if the atmospheric system were to be shifted a couple of degrees south, the American River Basin would experience much worse flooding than the actual historical 1997 case. Thus, it was decided to analyze what the maximum precipitation would be if the pineapple express system was shifted in latitudinal (meridional) or longitudinal (zonal) directions, and how much shift would be needed in order to obtain the maximum precipitation for the domain under study. In order to answer these questions, two experimental approaches are proposed: one is to shift the pineapple express in the meridional direction and the other is to shift it in the zonal direction. The main idea in the proposed exercise is similar to the replacement of the atmospheric conditions method described in a previous subsection where the shifted conditions are simulated over the study domain. For the meridional shift, six shifting positions were setup from the model domain origin with two degrees increments in both the north and the south directions in order to determine the initial and boundary conditions for these shifted domains. Then these shifted initial and boundary conditions were applied to the original domain in order not to lose the original topographical effects on precipitation. In other words, this numerical experiment is based on an atmospheric drift over the topography. The meridional experiment setup is

presented in Table 4.6. In the first column the shifted cases are named. For instance, 2° North means that the whole atmospheric conditions that are 2° North of the original domain, were simulated in place of conditions, corresponding to the original domain. The row that starts with the case name of the original location is recalled from the WRF column of Table 3.2 for the corresponding years. The latitude column gives the middle of the domain locations. There is no zonal shift in this experiment.

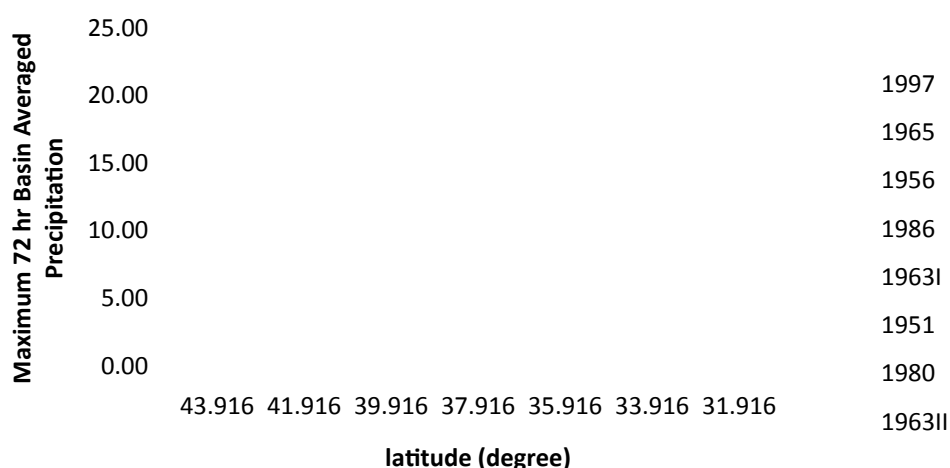


Figure 4.10 Meridionally shifted maximum precipitation (inches)

Meridional shifting of the pineapple express event simulation results show that the majority of the pineapple express events that render highest precipitation over AR Watershed, occur in the north of the American River Basin. For this reason, only this shift, from North to South, is applied to all 42 historical events. The results are presented in Table 4.6.

The Pineapple Express of 1963II case, which is the second event of water year 1963 as shown in Table 3.2, is different from others in that it has the similar magnitude for a wide range although its magnitude decreases from north to south (Table 4.6). The maximum

precipitation does not increase with meridional shifts for 1951 case. Among the studied cases, the maximum precipitation was obtained again for the 1965 case when the system that was 4 degrees north of the American river basin domain, was shifted to over the basin. Under such a scenario the basin-average 72-hr maximum precipitation would become 21.16 inches, which is the highest value obtained so far in this study (Figure 4.10).

Based on 8 historical cases shown in Figure 4.10 and Table 4.6, the maximum precipitation is obtained from the North to the South (NS) shift of the pineapple express instead of from the South to the North (SN) shift. On the other hand, there is no specific indicator about which NS shift is more pronounced to produce maximum precipitation. Therefore, all three NS shifts are applied to all 42 historical events in order to evaluate the net NS (from North to South) shift effect. The results are presented in Table 4.7.

Table 4.6 72-hr maximum basin averaged precipitation obtained by meridional shifting (inches)									
Case Name	Latitude	1951	1956	1963I	1963II	1965	1980	1986	1997
6° North	43.916° N	4.56	16.75	9.95	11.32	18.89	11.60	9.74	15.15
4° North	41.916° N	7.27	15.71	13.79	10.54	21.16	10.70	12.53	17.01
2° North	39.916° N	8.81	15.27	17.37	10.33	19.90	9.49	12.93	15.76
Original Location	37.916° N	10.29	13.08	13.78	9.59	15.00	8.06	12.54	11.48
2° South	35.916° N	7.81	12.07	4.49	10.31	9.35	7.90	10.76	10.67
4° South	33.916° N	2.87	2.86	0.83	11.21	2.90	7.38	8.66	8.39
6° South	31.916° N	0.03	0.64	0.01	8.90	0.66	6.62	4.93	5.67

After shifting the atmospheric conditions in the latitudinal direction, a similar shift in the longitudinal direction was considered. For the zonal shift, four shifting positions with respect to the origin of the model domain were setup with two-degree increments only from the West to the East, since the West sector of the domain is the source of the pineapple express mechanism.

The zonal experiment setup is presented in Table 4.8 similar to Table 4.6. For example, 8° West means that the atmospheric conditions that are at 8° West of the original domain, replace the conditions for the original domain during simulations. The original location column is identical to original location row of Table 4.6 for reference. The longitudes show the mid-points of the domains. There is no meridional shift in this experiment.

Zonal shifting of the pineapple express events show that in the majority of the pineapple express events precipitation increases with the shifting of the atmospheric conditions in the west direction with respect to AR Basin. The maximum precipitation does not increase with zonal shifting in the 1951 and 1963II cases. Among the studied cases, the maximum precipitation is obtained again for the 1965 case when the historical atmospheric system that is located 6 degrees west of the original domain over the AR basin domain, is shifted over the basin. In this scenario the basin average 72-hr maximum precipitation would become 20.33 inches (Table 4.8 and Figure 4.11).

Table 4.7 72-hr maximum basin averaged precipitation obtained by meridional shifting for 42 historical events (inches)

Water Y	Month	Day	Year	Historical	2° N	4° N	6° N
1951	11	20	1950	10.29	8.81	7.27	4.56
1956	12	23	1955	13.08	15.27	15.71	16.75
1963I	10	13	1962	13.78	17.37	13.79	9.95
1963II	2	1	1963	9.59	10.33	10.54	11.32
1965	12	23	1964	15.00	19.90	21.16	18.89
1966	11	18	1965	3.08	3.90	2.73	3.68
1967	1	22	1967	7.72	9.65	9.59	8.75
1968	2	21	1968	4.29	6.27	9.17	9.78
1969	1	21	1969	5.85	13.49	7.65	3.12
1970	1	16	1970	4.14	4.34	6.48	5.92
1971	12	3	1970	6.15	8.85	8.96	7.38
1972	12	24	1971	3.95	4.09	5.74	7.62
1973	1	18	1973	6.22	6.11	5.52	5.39
1974	11	12	1973	7.39	7.95	8.65	12.39
1975	2	3	1975	7.08	6.43	5.98	4.87
1976	10	27	1975	2.02	4.20	5.85	5.98
1977	1	3	1977	2.71	3.54	3.15	2.30
1978	1	16	1978	7.10	6.29	4.42	3.01
1979	1	12	1979	4.73	5.01	5.95	5.53
1980	1	13	1980	8.06	9.49	10.70	11.60
1981	1	29	1981	6.52	5.13	4.07	3.60
1982	2	15	1982	8.88	10.40	12.01	12.83
1983	12	22	1982	7.29	7.35	7.50	7.55
1984	12	26	1983	7.99	6.86	4.84	3.40
1985	2	10	1985	5.39	5.22	5.17	4.81
1986	2	18	1986	12.54	12.93	12.53	9.74
1987	2	13	1987	3.26	4.47	5.56	5.81
1988	4	21	1988	3.11	1.78	1.64	1.82
1989	11	25	1988	6.76	8.29	8.63	8.73
1990	11	26	1989	2.68	3.34	3.79	4.45
1991	3	3	1991	7.21	7.48	7.02	7.02
1992	2	16	1992	3.79	2.32	2.34	2.49
1993	12	11	1992	5.41	6.26	8.16	7.24
1994	2	20	1994	3.94	3.18	3.65	5.96
1995	3	12	1995	9.80	10.59	9.66	8.79
1996	12	13	1995	7.10	10.18	13.10	11.05
1997	1	3	1997	11.48	15.76	17.01	15.15
1998	1	13	1998	4.36	5.64	5.79	6.44
1999	2	9	1999	9.15	8.07	7.74	8.42
2000	2	14	2000	7.14	8.66	7.67	5.62
2001	2	12	2001	3.80	3.16	2.20	0.97
2002	12	3	2001	4.30	5.40	6.37	5.91

Case Name	8° West	6° West	4° West	2° West	Original Location
Longitude	130° W	128° W	126° W	124° W	122° W
1951	9.90	9.67	9.62	9.62	10.29
1956	19.63	19.90	17.56	14.65	13.08
1963I	8.37	10.71	13.72	19.10	13.78
1963II	8.55	8.39	7.30	7.88	9.59
1965	19.09	20.33	19.95	18.21	15.00
1980	7.22	8.53	8.67	8.40	8.06
1986	10.55	12.13	13.33	14.79	12.54
1997	10.47	13.39	13.27	12.28	11.48

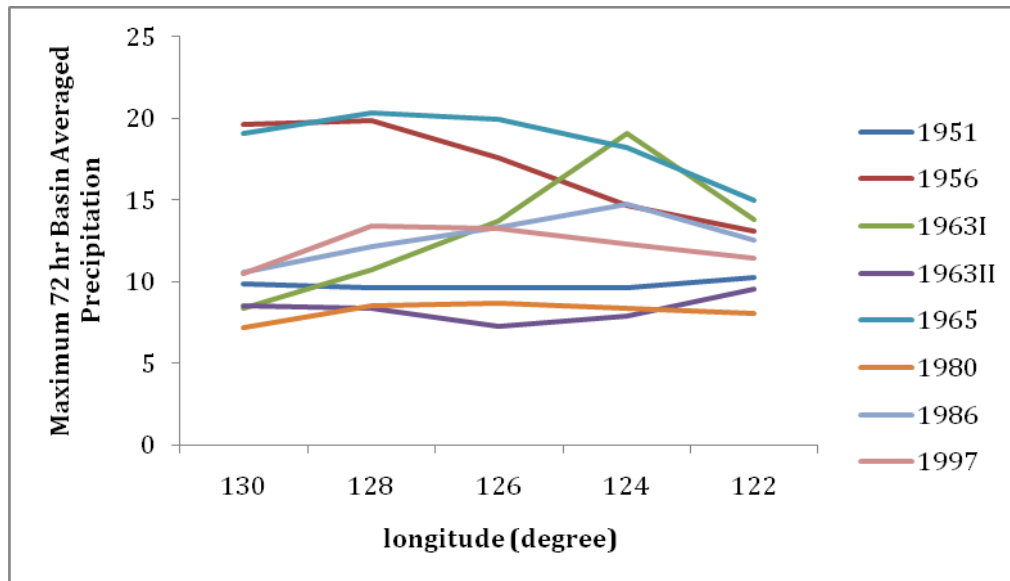


Figure 4.11 Zonally shifted maximum precipitation (inches)

Figure 4.11 shows that the maximum precipitation is the highest around 8 degrees west shift. Therefore, this shift is applied to all 42 historical events in order to evaluate the net west-shift effect. The results are presented in Table 4.9.

It is seen from Tables 4.6, 4.7, 4.8 and 4.9 that a small spatial shift in the pineapple express synoptic conditions would have caused a substantial increase in maximum precipitation, based on the historical records for the American River Watershed. However, based on these four tables, the maximum precipitation over the American River Basin in the case of the 1951 Pineapple Express (PE) event, corresponds to the original meridional and zonal locations, where shifting had no influence. As shown in Figures 4.1, 4.2 and 4.3, the PE events generally occur in the southwest-northeast direction. Thus, in the discussed experiments the PE was shifted from northwest to the original location in order to show that maximum precipitation can be obtained from a northwest shift. For the 1997 case, 17.17 inches of maximum precipitation was obtained by this shifting mechanism. This is the highest amount obtained so far in this study for the 1997 case.

Consequently, one of the most significant outcomes of this experiment is that the maximum precipitation occurs when the PE mechanism hits the AR Watershed directly, and the amount of this maximum depends on the intensity of the PE with respect to both moisture and wind.

Table 4.9 72-hr maximum basin averaged precipitation obtained by zonal shifting for all 42 historical events (inches)

Water Y	Month	Day	Year	Historical	6° W
1951	11	20	1950	10.29	9.67
1956	12	23	1955	13.08	19.90
1963I	10	13	1962	13.78	10.71
1963II	2	1	1963	9.59	8.39
1965	12	23	1964	15.00	20.33
1966	11	18	1965	3.08	2.42
1967	1	22	1967	7.72	8.01
1968	2	21	1968	4.29	9.46
1969	1	21	1969	5.85	5.85
1970	1	16	1970	4.14	7.78
1971	12	3	1970	6.15	7.64
1972	12	24	1971	3.95	5.85
1973	1	18	1973	6.22	5.62
1974	11	12	1973	7.39	5.12
1975	2	3	1975	7.08	4.51
1976	10	27	1975	2.02	3.07
1977	1	3	1977	2.71	1.83
1978	1	16	1978	7.10	6.74
1979	1	12	1979	4.73	8.01
1980	1	13	1980	8.06	8.53
1981	1	29	1981	6.52	3.02
1982	2	15	1982	8.88	14.91
1983	12	22	1982	7.29	6.79
1984	12	26	1983	7.99	9.62
1985	2	10	1985	5.39	3.86
1986	2	18	1986	12.54	12.13
1987	2	13	1987	3.26	6.26
1988	4	21	1988	3.11	5.79
1989	11	25	1988	6.76	9.04
1990	11	26	1989	2.68	3.21
1991	3	3	1991	7.21	8.87
1992	2	16	1992	3.79	3.73
1993	12	11	1992	5.41	9.27
1994	2	20	1994	3.94	4.41
1995	3	12	1995	9.80	7.29
1996	12	13	1995	7.10	8.23
1997	1	3	1997	11.48	13.39
1998	1	13	1998	4.36	6.61
1999	2	9	1999	9.15	9.03
2000	2	14	2000	7.14	8.57
2001	2	12	2001	3.80	2.73
2002	12	3	2001	4.30	4.83

4.3.4 Thermodynamically possible worst-case scenario creation

The last proposed maximization approach is to ascertain the physically possible worst-case scenarios for the basin of interest, and to examine their pertinence to realistic conditions. For this purpose the WRF model was used in order to determine an upper limit for the maximum possible precipitation.

The first attempt is to evaluate the cases where either the whole atmosphere is initially saturated or the winds are at highest possible speeds. Although it is thermodynamically possible that an atmospheric column can reach saturation or even supersaturation, it is difficult to determine a physically possible upper limit for the wind speed, especially considering that its maximum depends on height. Therefore, here only the cases where the whole atmospheric column is saturated, are created. This scenario, first, was applied to five high-ranked historical flood events and the obtained maximum precipitation amounts with their corresponding precipitable water values are shown in Table 4.10. Then, 100% saturated atmosphere scenario is applied to all 42 historical events whose results are presented in Table 4.11.

For the five high ranked historical flood events, the precipitable water values of Table 4.10 are higher than those of Table 4.11, since in Table 4.10 precipitable water values are for saturated atmospheric conditions.

The results presented in Tables 4.10 and 4.11 show that simulation of a saturated atmosphere has not necessarily rendered the highest possible precipitation. For instance, for the case of 1997, the maximum precipitation for the fully-saturated atmosphere is not higher than what was obtained from the shifting method.

Table 4.10 72-hr maximum basin-averaged precipitation under the saturated atmosphere (100% RH) conditions

Water Year	Maximum Precipitation (in)	Precipitable Water (in)
1956	17.03	52.41
1963I	22.35	79.43
1965	20.31	73.79
1986	17.82	54.53
1997	15.79	53.12

A similar conclusion holds true for the case of 1965 event. Hence, the creation of the saturated atmospheric conditions does not necessarily lead to an upper limit for maximum precipitation.

It is important to note that 1963I event yields the highest precipitation (22.35 inches) among all studied cases and maximization methods but precipitable water calculations. The probability of exceedance of this highest precipitation is going to be determined in the next chapter in order to quantify the physically possible PMP for the American River Watershed.

Table 4.11 Maximized precipitation for all 42 historical cases (inches)

Water Y	Month	Day	Year	Historical	2° N	4° N	6° N	6° W	RH
1951	11	20	1950	10.29	8.81	7.27	4.56	9.67	12.41
1956	12	23	1955	13.08	15.27	15.71	16.75	19.90	17.03
1963I	10	13	1962	13.78	17.37	13.79	9.95	10.71	22.35
1963II	2	1	1963	9.59	10.33	10.54	11.32	8.39	15.77
1965	12	23	1964	15.00	19.90	21.16	18.89	20.33	20.31
1966	11	18	1965	3.08	3.90	2.73	3.68	2.42	10.65
1967	1	22	1967	7.72	9.65	9.59	8.75	8.01	12.70
1968	2	21	1968	4.29	6.27	9.17	9.78	9.46	5.41
1969	1	21	1969	5.85	13.49	7.65	3.12	5.85	11.97
1970	1	16	1970	4.14	4.34	6.48	5.92	7.78	9.52
1971	12	3	1970	6.15	8.85	8.96	7.38	7.64	8.54
1972	12	24	1971	3.95	4.09	5.74	7.62	5.85	12.02
1973	1	18	1973	6.22	6.11	5.52	5.39	5.62	11.67
1974	11	12	1973	7.39	7.95	8.65	12.39	5.12	12.21
1975	2	3	1975	7.08	6.43	5.98	4.87	4.51	8.56
1976	10	27	1975	2.02	4.20	5.85	5.98	3.07	4.57
1977	1	3	1977	2.71	3.54	3.15	2.30	1.83	4.20
1978	1	16	1978	7.10	6.29	4.42	3.01	6.74	13.36
1979	1	12	1979	4.73	5.01	5.95	5.53	8.01	5.94
1980	1	13	1980	8.06	9.49	10.70	11.60	8.53	15.39
1981	1	29	1981	6.52	5.13	4.07	3.60	3.02	9.22
1982	2	15	1982	8.88	10.40	12.01	12.83	14.91	11.70
1983	12	22	1982	7.29	7.35	7.50	7.55	6.79	11.67
1984	12	26	1983	7.99	6.86	4.84	3.40	9.62	9.30
1985	2	10	1985	5.39	5.22	5.17	4.81	3.86	6.42
1986	2	18	1986	12.54	12.93	12.53	9.74	12.13	17.82
1987	2	13	1987	3.26	4.47	5.56	5.81	6.26	6.42
1988	4	21	1988	3.11	1.78	1.64	1.82	5.79	4.09
1989	11	25	1988	6.76	8.29	8.63	8.73	9.04	9.34
1990	11	26	1989	2.68	3.34	3.79	4.45	3.21	4.98
1991	3	3	1991	7.21	7.48	7.02	7.02	8.87	14.66
1992	2	16	1992	3.79	2.32	2.34	2.49	3.73	5.21
1993	12	11	1992	5.41	6.26	8.16	7.24	9.27	10.08
1994	2	20	1994	3.94	3.18	3.65	5.96	4.41	8.70
1995	3	12	1995	9.80	10.59	9.66	8.79	7.29	15.80
1996	12	13	1995	7.10	10.18	13.10	11.05	8.23	16.03
1997	1	3	1997	11.48	15.76	17.01	15.15	13.39	15.79
1998	1	13	1998	4.36	5.64	5.79	6.44	6.61	6.89
1999	2	9	1999	9.15	8.07	7.74	8.42	9.03	12.24
2000	2	14	2000	7.14	8.66	7.68	5.62	8.57	10.84
2001	2	12	2001	3.80	3.16	2.20	0.97	2.73	6.25
2002	12	3	2001	4.30	5.40	6.37	5.91	4.83	11.60

It was defined in Chapter I (Equation 1.4) that an integration of the specific humidity of water vapor yields the precipitable water, which is a depth of water that is obtained if the water vapor of the whole atmospheric column condenses. This hypothetical term gives the upper limit of that condensation amount. Analogously, it may be hypothesized that the upper limit of the probable maximum precipitation can be obtained from

$$PW_r = \frac{1}{g\rho_w} \int_0^{p_0} q_{rain} dp \quad (4.17)$$

where PW_r is precipitable water which is the upper limit of PMP for an atmospheric column, assuming that all rainwater reaches the ground. It is important to note that q_{rain} gives more realistic results than $q_{\text{water vapor}}$ as was mentioned in the modeling of the MFC subsection. This new equation (4.14) was applied to all 42 historical cases in order to obtain the maximum 72-hr basin-averaged PMP values. q_{rain} , which is one of the outputs from the WRF model, is integrated from surface to the top of the atmosphere at each grid cell over AR Watershed as shown in equation 4.17 and the resultant PW values are interpolated to AR Watershed in order to obtain 72-hr basin average depths. Equation 4.17 may be taken as the upper limit of probable maximum precipitation since all PMP depths are greater than the maximum precipitation amounts that were previously computed by various maximization approaches for the 42 cases as shown in Table 4.12.

Although modeled precipitable water may be assumed as the upper limit of PMP, it may not be realistic to have all the precipitable water as rain due to actual microphysical processes. It is true that precipitable water is the upper limit and it is not physically possible

to reach it, but it is, in the end, a hypothetical term. As one can see from Table 4.12, it might be very costly to determine precipitable water as PMP. In the next chapter, the probability of exceedance of this highest limit shall be discussed.

Table 4.12 72-hr maximum basin-averaged precipitable water (inches)					
Water Year	Precipitable Water	Water Year	Precipitable Water	Water Year	Precipitable Water
1951	34.92	1975	10.65	1989	22.92
1956	38.58	1976	8.23	1990	6.38
1963I	53.05	1977	10.59	1991	23.53
1963II	31.15	1978	18.78	1992	7.97
1965	58.96	1979	20.86	1993	17.59
1966	12.68	1980	27.36	1994	7.70
1967	20.08	1981	13.32	1995	26.90
1968	19.18	1982	31.60	1996	24.58
1969	21.51	1983	18.50	1997	31.01
1970	15.29	1984	28.18	1998	17.14
1971	14.31	1985	11.86	1999	26.07
1972	8.66	1986	51.48	2000	21.23
1973	15.87	1987	13.96	2001	6.60
1974	26.09	1988	11.14	2002	13.87

4.4 Climate Change Effect on Precipitation of the American River Watershed

As was discussed in the first chapter, climate change is not the main focus of this study. Here, the objective is to provide first impressions about how precipitation for the American River Watershed would change depending upon temperature increase.

According to climate change projections, changes are expected in precipitation regarding both frequency and intensity for the next hundred years depending on the location. For California, the resolution issue is one of the most significant flaws of climate models, since

only two computational grids cover California in these models. This means that climate models cannot handle microphysical, land and boundary layer processes at sufficient accuracy, as of the mesoscale models. Therefore, more reasonable climate change studies are needed to make conclusions about extreme events. As a solution to the resolution problem, mesoscale models were recently adopted as climate models for performing dynamical downscaling of the Global Climate Model (GCM) simulations to an area of interest. This is similar to the analysis being presented here in order to obtain more realistic results. For instance HRL lab of UC Davis performs such a study for Northern California [M. L. Kervas, 2009, personal communication]. Such studies will provide a realistic insight about precipitation change in terms of both frequency and especially intensity. Being aware of these limitations, here only the temperatures are changed, according to the projections reported in other studies. Then under these changed temperature conditions the WRF model is run, and its simulation results are reported and discussed below.

4.4.1 Effect of Temperature Change

Projected global average surface temperature change with respect to different climate change scenarios for 2090-2099 time period relative to 1980-1999 is shown in Table 4.13 [IPCC, AR4].

In order to assess how precipitation changes with increasing temperatures, the WRF simulations were performed under corresponding best temperature change estimates, shown in Table 4.13, assuming that temperature of the whole atmospheric column will increase by these best estimates.

Table 4.13 Climate change effect on maximum precipitation based on the 1997 case		
Case	Temperature Change (Best Estimate)	WRF Maximum Precipitation (inches)
Constant year 2000 concentrations	0.6	12.11
B1 Scenario	1.8	13.33
A1T scenario	2.4	13.95
B2 scenario	2.4	13.95
A1B scenario	2.8	14.39
A2 scenario	3.4	15.33
A1FI scenario	4.0	15.87
Max Range of A1FI scenario	6.4	17.54

The results in Table 4.13 and Figure 4.12 show that the increase in temperature yields a highly linear increase in precipitation over the American River Watershed. The maximum precipitation, which is obtained according to the worst (leading to warmest conditions) climate scenario A1FI, is close to the amount obtained by some of the above-presented maximization methods. From this result it may be inferred that the magnitude of maximum winter precipitation may increase substantially with the change in climate.

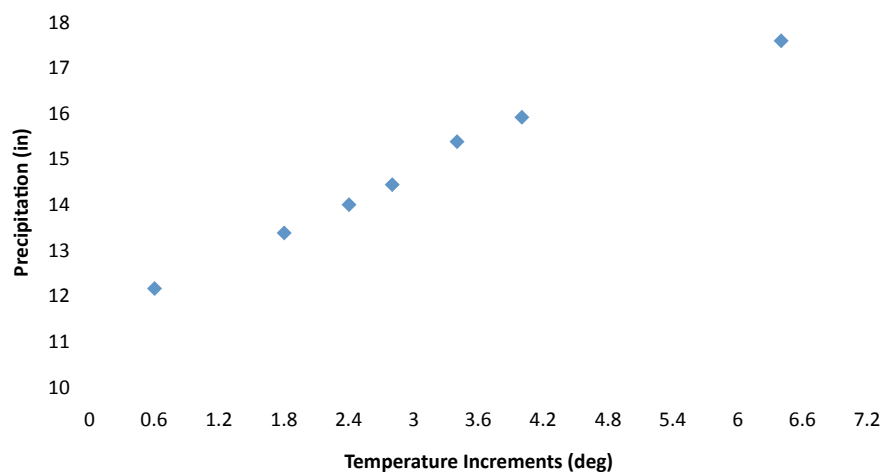


Figure 4.12 72-hr maximum basin-averaged precipitation change with the increase in temperature

4.5 Chapter Conclusions

Contrary to the belief that numerical weather prediction models cannot be used for the determination of probable maximum precipitation, although they are believed to be helpful in a limited way, in this chapter maximization techniques that can be utilized in practice were developed and tested.

It was first demonstrated that the occurrence of extreme precipitation not only depends on the existence of the Pineapple Express synoptic mechanism but it also needs appropriate moisture and wind conditions, resulting in moisture flux convergence to a specified basin. Here, it is shown that moisture convergence is highly correlated to precipitation.

In this chapter four precipitation maximization methods were proposed: 1. Perturbation of atmospheric conditions; 2. Shifting atmospheric conditions in space; 3. Exchange of atmospheric conditions among historical events; and 4. Thermodynamically possible worst-case scenario creation. The first three methods were investigated in detail numerically by means of the WRF regional atmospheric model simulations in order to assess how much one can maximize the historical precipitation amounts. In the last method, an attempt was made to develop a worst-case upper bound for probable maximum precipitation using the WRF. Finally, the effect of climate change on precipitation was investigated briefly by means a study on the net effect of temperature increase on winter precipitation over the American River Watershed.

A summary of the results, classified according to the methods presented in this chapter, is displayed in Table 4.14 below, based only on the 1997 historical event case.

Table 4.14 Precipitation maximization methods and their basin averaged values for the 1997 historical event (11.48 inches)									
Method I- Perturbation			Method II- Shifting			Method III- Replacement	Method IV- Worst scenario		Climate Change Effect
Moisture Only	Wind Only	Moisture and Wind	North-South	West-East	NW-SE	Atm vs Land	100% RH	Precipitable Water	Upper A1FI
14.31	15.79	19.47	17.01	13.39	17.17	12.124	15.79	31.01	17.54

Chapter V

Results and Discussions

Meteorological Analysis, Prediction, and Research Committee of the National Research Council Atmospheric Sciences and Climate Board has briefly discussed the issues concerning the determination of PMP, extreme precipitation events, and alternatives to PMP [*National Research Council*, 1994]. In this chapter, the discussions of that assessment report (hereafter NRC94), are evaluated in detail. During this evaluation, the assumptions made in the traditional method will be challenged, and the improvements by the newly-developed method will be discussed in terms of these assumptions and their validity.

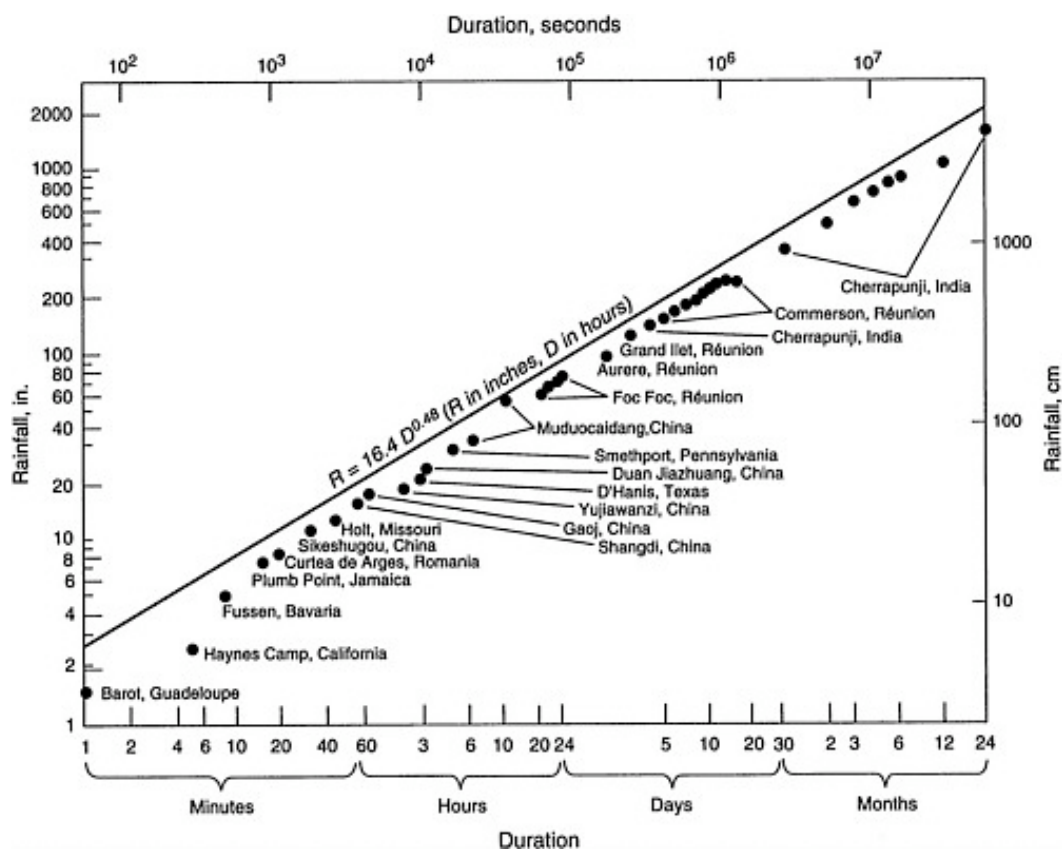


Figure 5.1. Maximum observed point rainfalls as a function of duration (Courtesy of John Vogel, National Weather Service [NRC94])

NRC94 suggests that the very conservative version of PMP can be determined by using Figure 5.1, which shows the maximum observed rainfalls at specific locations as a function of duration, under the assumption of “in any given amount of time the greatest precipitation would be bounded by the greatest precipitation accumulation observed anywhere in the world for that duration.” However, *NRC94* is aware that using this approach would be so costly that no one could afford it. Furthermore, there is no physical justification that any new storm may not exceed those maximum amounts shown in Figure 5.1, especially when one considers climate change. As was discussed in previous chapters, it is possible to determine very high PMP values, which may never occur. However, what is sought is an optimum approach that is both highly efficient and less costly. Therefore, the efforts that try to find local PMP values would be more beneficial than those that try to determine universal PMP values, independent of space. Consequently, one ends up with a time-and-space problem of PMP.

Traditional PMP procedures are mainly based on two approaches: storm transposition and moisture maximization. The proposed method here also originates from these two approaches with the aim of reducing assumptions made in the traditional method. It would be more appropriate to call the second approach as moisture flux maximization, since not only the moisture maximization, but also the wind maximization is a crucial component in PMP calculations, as was demonstrated in the previous chapter.

The main idea of the traditional storm transposition approach is to determine a hypothetical storm rainfall for a basin of interest, using the historical storms that have occurred over or the surrounding region of that basin. As one may appreciate, the PMP may not necessarily be obtained by using this approach [*Myers*, 1967]. As a counterpart of this approach, in this study the shifting method of the atmospheric conditions was utilized. With

this method it is possible to obtain maximum precipitation values since very large areas are spanned both longitudinally and latitudinally in order to find the atmospheric conditions that may lead to maximum precipitation under the observed conditions of the historical storm. The other novelty of the method here is that it is physically based in terms of storm movement. The traditional transposition method uses a transposition factor that is determined by rainfall data. As mentioned earlier, rainfall data could be misleading due to local effects (i.e. lack of stations due to orography, station location change, etc.) and measurement failures (i.e. wind effect, tipping bucket change during the storm, etc.). Although it is assumed that the data are correct, transposition factors are calculated by only using the recorded rainfall data. However, same storms could precipitate differently depending upon many effects (such as terrain effect, etc.), which are not accounted for in the traditional method. The implicit assumption of the transposition method, that the atmospheric conditions are uniform and isotropic, is no longer valid based upon the above-reported findings of this study.

In the traditional moisture maximization approach, another goal is to maximize precipitation locally under the assumption that precipitation is linearly related to the precipitable water. This relation is discussed in equation 1.3 which needs to be modified as:

$$P_{\max} = \left(\frac{PW_{\max}}{PW} \right) \times P \quad (5.1)$$

where $P_{\max}$ is probable maximum precipitation, P is observed rainfall, PW is precipitable water, and $PW_{\max}$ is the maximized precipitable water as given by the maximum 24-hour persisting dew points [Wiesner, 1970].

Equation 5.1 can also be written as,

$$\frac{P_{\max}}{PW_{\max}} = \frac{P}{PW} \quad (5.2)$$

On the other hand, *Abbs* [1999] found that the precipitation is not linearly related to the precipitable water. In order to demonstrate how precipitable water changes with precipitation, a scatter plot, based on the WRF model-estimated precipitable water versus the WRF model estimated precipitation for the 42 historical extreme precipitation cases, was constructed and is illustrated in Figure 5.2.

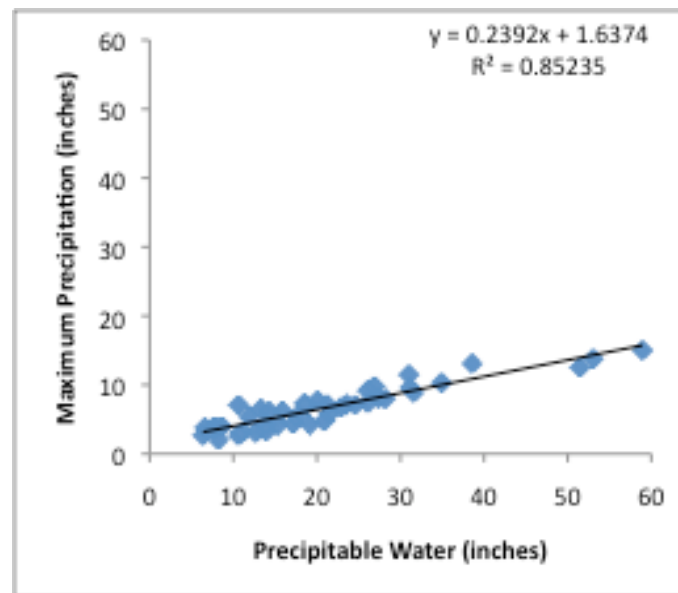


Figure 5.2 Precipitable Water vs. Precipitation (inches)

In Figure 5.2, the precipitable water values were obtained from Table 4.12, and the corresponding precipitation values were obtained from Table 3.2. Contrary to the results of *Abbs* [1999], Figure 5.2 shows that precipitation is highly linearly related to the precipitable water, yet this does not mean that Equation 5.1 is valid. In order to discuss the validity of

Equation 5.1 or Equation 5.2, Table 5.1 was constructed based on 42 historical extreme flood events. The third column of Table 5.1 gives the ratio of the maximum precipitation to maximum precipitable water, which corresponds to the left hand side of the Equation 5.2. Maximum precipitation and maximum precipitable water values are the model results of 4-degree shift from North to South method, since 4-degree NS shift method provides the highest physically possible precipitation overall. The fourth column of Table 5.1 is the ratio of precipitation to precipitable water, which corresponds to the right hand side of Equation 5.2. Precipitation and precipitable water values correspond to the WRF model results of historical events. According to Equation 5.2 these two columns should be identical, but as presented in Table 5.1, these two ratios can be assumed equal only for some cases such as the case of the 1956, 1992, and 1997 storm events (Figure 5.3). Consequently, approximated PMP values shown in the table are not identical to the maximized values by using atmospheric modeling approach. “PMP modeled” column of Table 5.1 shows the model results of 4-degree NS shifted method. The last column of Table 5.1, “PMP approximated”, is constructed using Equation 5.1. The comparison of PMP modeled and approximated values (Figure 5.4) indicate that Equation 5.1 is not even approximately valid for the 1965 historical storm case, which is the highest in record. Therefore, the main assumption of the traditional PMP method is just a coarse approximation, which underestimates maximum precipitation for the majority of the historical events.

Table 5.1 The validity of the main assumption of the traditional PMP methods					
Storm Number	Water Year	Pmax/PWmax	P/PW	PMP modeled	PMP approximated
1	1951	0.78	0.29	7.27	2.76
2	1956	0.36	0.34	15.71	14.74
3	1963I	0.38	0.26	13.79	9.43
4	1963II	0.46	0.31	10.54	6.99
5	1965	0.37	0.25	21.16	14.59
6	1966	0.42	0.24	2.73	1.58
7	1967	0.59	0.38	9.59	6.27
8	1968	0.28	0.22	9.17	7.26
9	1969	0.60	0.27	7.65	3.50
10	1970	0.46	0.27	6.48	3.86
11	1971	0.55	0.43	8.96	6.96
12	1972	0.76	0.46	5.74	3.42
13	1973	0.50	0.39	5.52	4.30
14	1974	0.35	0.28	8.65	7.08
15	1975	0.91	0.66	5.98	4.35
16	1976	0.58	0.24	5.85	2.48
17	1977	0.43	0.26	3.15	1.86
18	1978	0.41	0.38	4.42	4.12
19	1979	0.31	0.23	5.95	4.31
20	1980	0.67	0.29	10.70	4.71
21	1981	0.45	0.49	4.07	4.41
22	1982	0.38	0.28	12.01	8.88
23	1983	0.53	0.39	7.50	5.59
24	1984	0.37	0.28	4.84	3.71
25	1985	0.80	0.45	5.17	2.95
26	1986	0.48	0.24	12.53	6.40
27	1987	0.32	0.23	5.56	4.02
28	1988	0.41	0.28	1.64	1.12
29	1989	0.51	0.30	8.63	5.03
30	1990	0.51	0.42	3.79	3.13
31	1991	0.40	0.31	7.02	5.33
32	1992	0.45	0.48	2.34	2.45
33	1993	0.45	0.31	8.16	5.63
34	1994	0.76	0.51	3.65	2.45
35	1995	0.47	0.36	9.66	7.46
36	1996	0.44	0.29	13.10	8.54
37	1997	0.38	0.37	17.01	16.76
38	1998	0.40	0.25	5.79	3.65
39	1999	0.63	0.35	7.74	4.31
40	2000	0.38	0.34	7.68	6.75
41	2001	0.40	0.58	2.20	3.19
42	2002	0.39	0.31	6.37	5.07

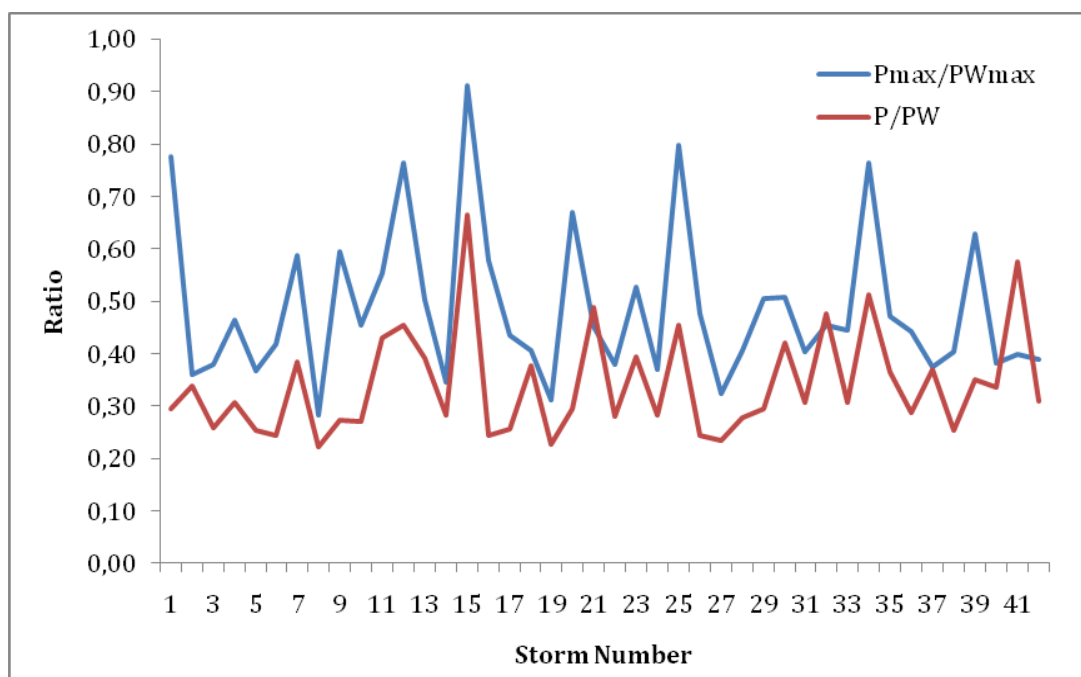


Figure 5.3 Time series of the ratios of precipitation to precipitable water

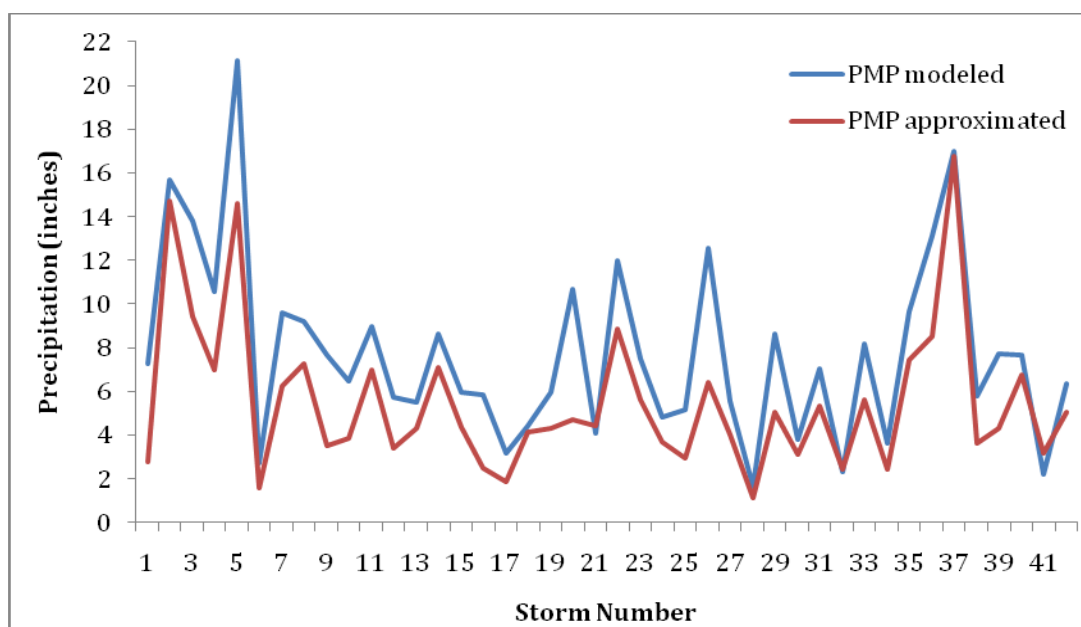


Figure 5.4 Time series of the modeled and approximated PMP

Moreover, the maximum precipitable water values, estimated in this study, are based on the WRF model outputs, whereas the Maximum Precipitable Water calculations of the

traditional method are determined from the surface dew point temperature which is a poor indicator of precipitable water, as mentioned in NRC [1994] report (please see literature review for detailed discussion of precipitable water). Therefore, one may infer that the approximations of Equation 5.1 or Equation 5.2 may be less accurate with the calculations of the traditional methods.

As the last effort of this dissertation, an optimum precipitation maximization method and therefore a physically possible optimum PMP is sought for highly efficient and less costly design purposes. For this purpose, the feasibility of proposed maximization methods is discussed in this section by means of relative frequency histograms and the complementary cumulative distribution functions (CCDF), i.e, exceedance probabilities of the historically maximized precipitation events. After the determination of the most feasible maximization method, the statistical distribution of the historically maximized precipitation of that method shall be presented in order to investigate the return periods in terms of reliability and expected design life.

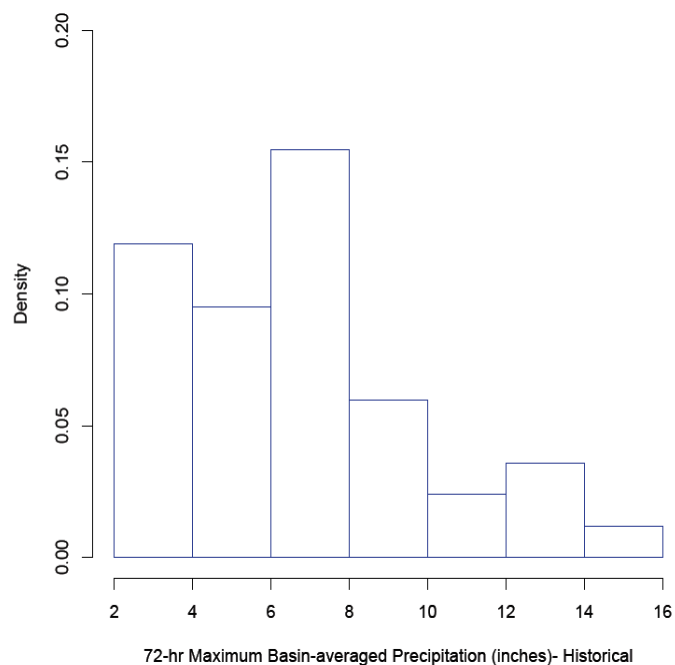


Figure 5.5 Relative frequency histogram of 72-hr maximum basin averaged precipitation for the historical storms at the ARW

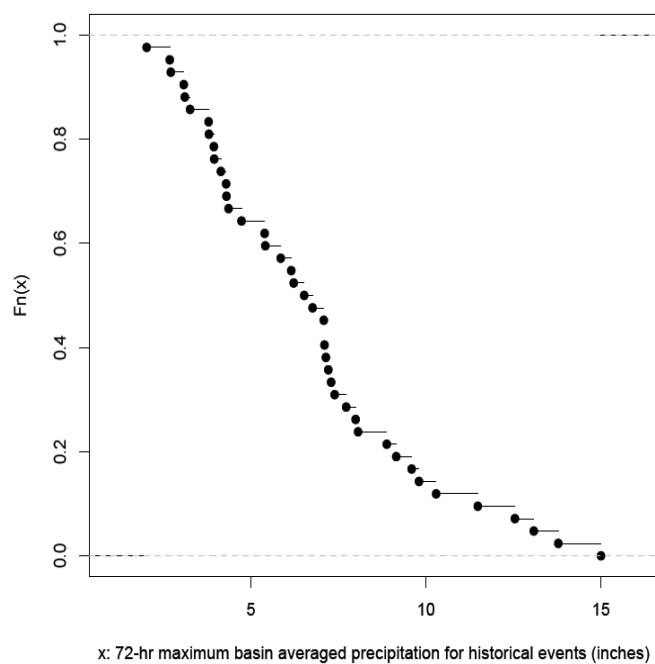


Figure 5.6 Exceedance probability distribution of 72-hr maximum basin averaged precipitation for historical storms at the ARW

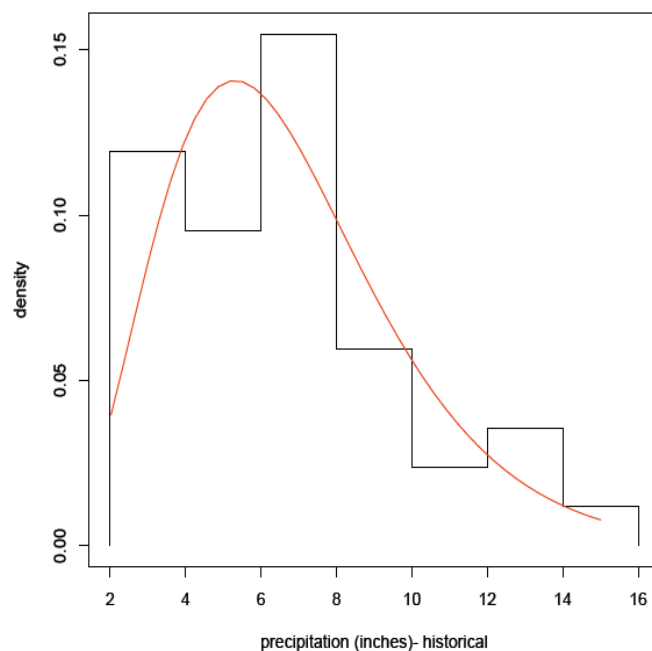


Figure 5.7 Gamma distribution fitted to the relative frequency histogram of 72-hr maximum basin averaged precipitation for the historical storms at the ARW

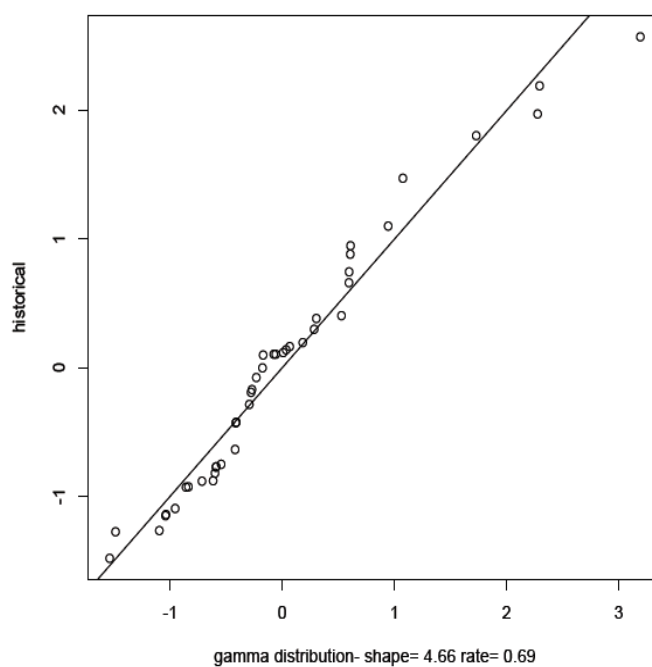


Figure 5.8 Q-Q plot for historical storms at the ARW

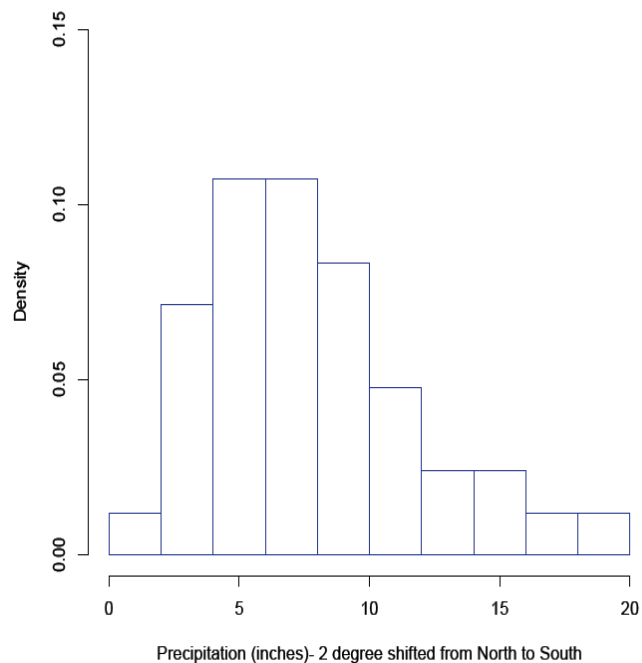


Figure 5.9 Relative frequency histogram of 72-hr maximum basin averaged precipitation for the historical storms at AR Watershed after a 2 degrees shift from N to S

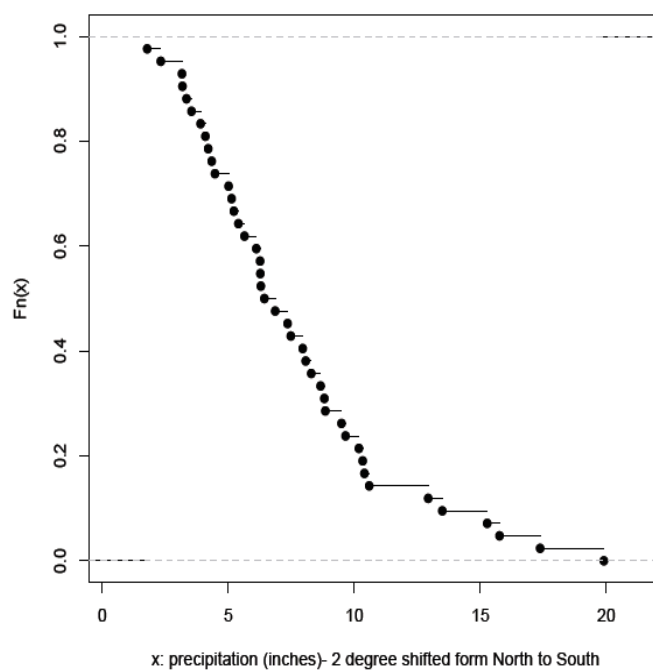


Figure 5.10 Exceedance probability distribution of 72-hr maximum basin averaged precipitation for historical storms at the ARW after a 2 degrees N to S shift

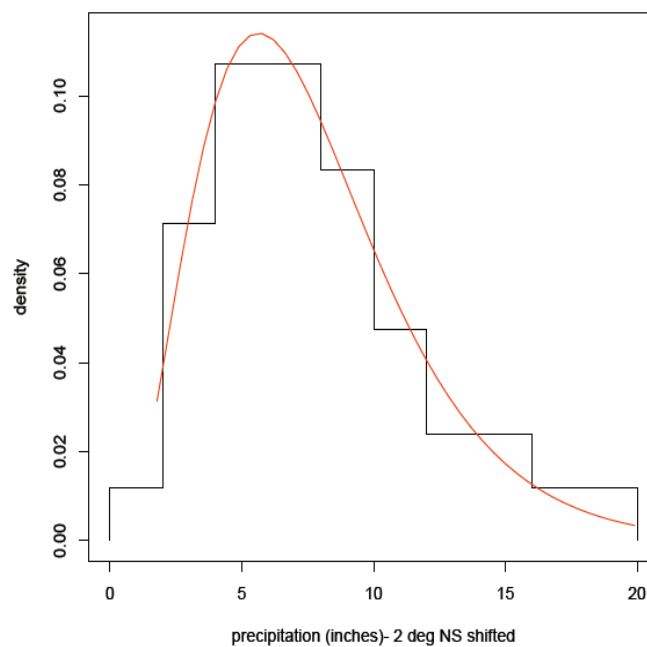


Figure 5.11 Gamma distribution fitted to the relative frequency histogram of 72-hr maximum basin averaged precipitation for the historical storms at the ARW after a 2 degrees NS shift

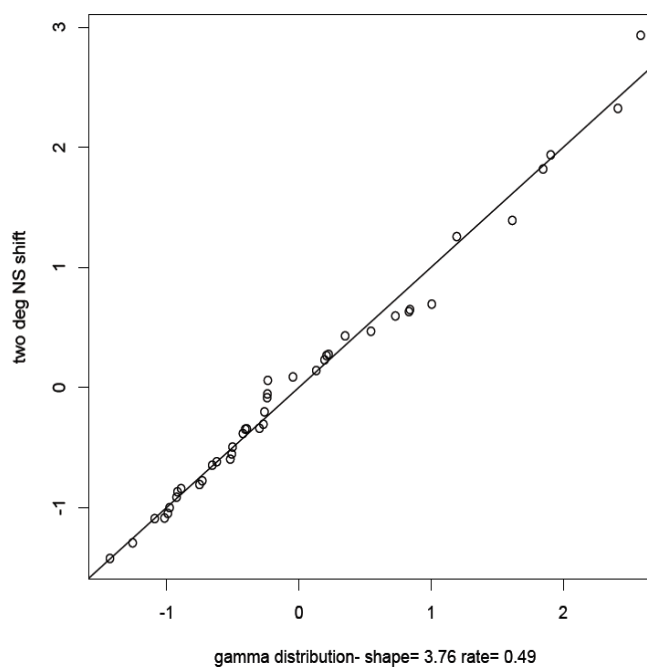


Figure 5.12 Q-Q plot for historical storms after a 2 degrees N to S shift

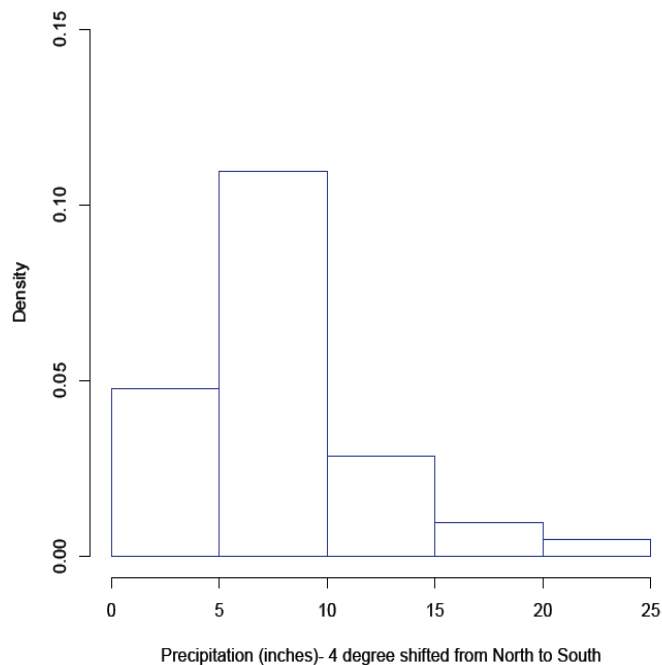


Figure 5.13 Relative frequency histogram of 72-hr maximum basin averaged precipitation for the historical storms at the ARW after a 4 degrees shift from N to S

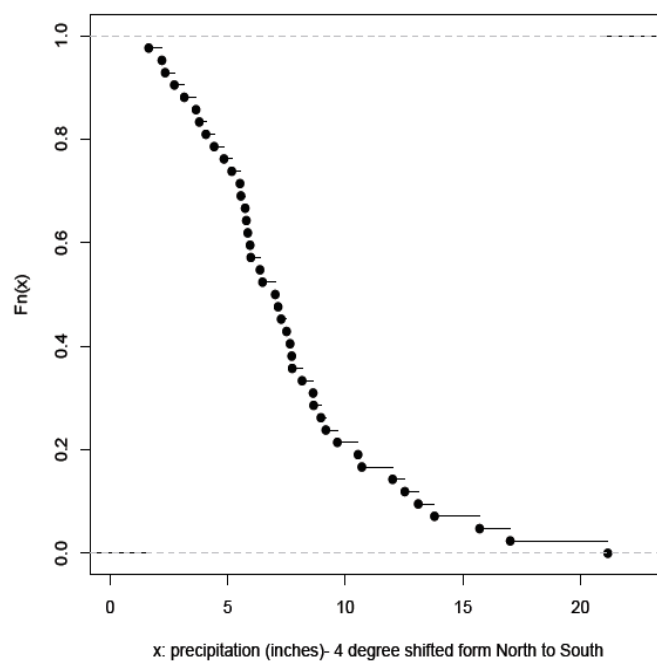


Figure 5.14 Exceedance probability distribution of 72-hr maximum basin averaged precipitation for historical storms at the ARW after a 4 degrees N to S shift

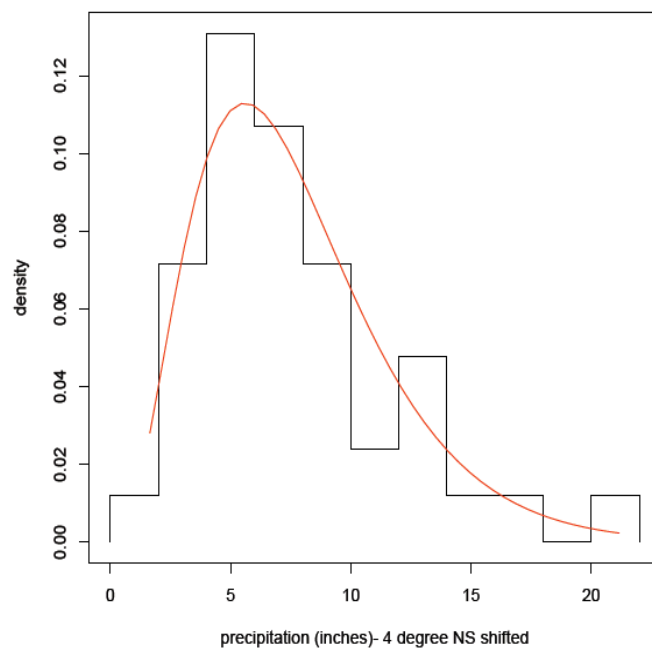


Figure 5.15 Gamma distribution fitted to the relative frequency histogram of 72-hr maximum basin averaged precipitation for the historical storms at the ARW after a 4 degrees N to S shift

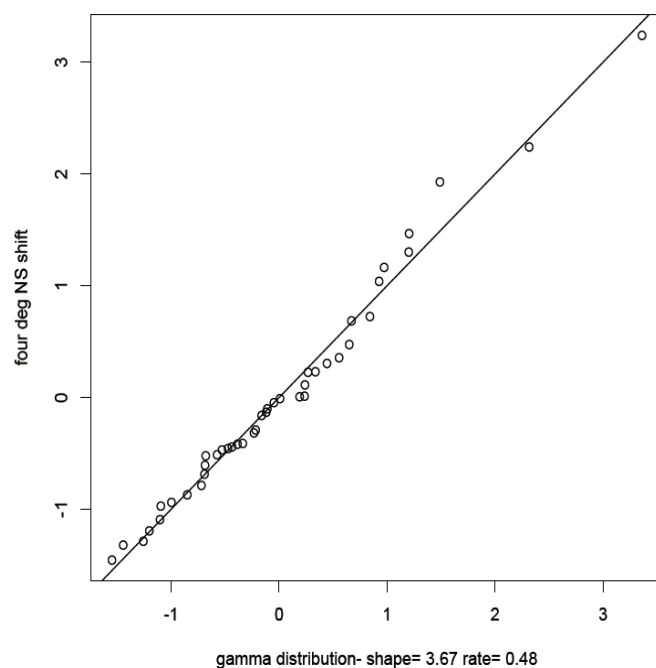


Figure 5.16 Q-Q plot for historical storms after a 4 degrees N to S shift

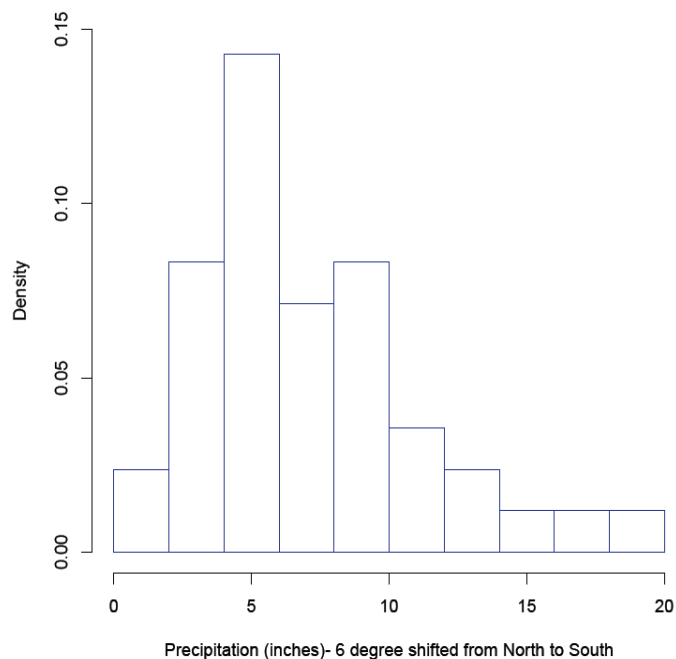


Figure 5.17 Relative frequency histogram of 72-hr maximum basin averaged precipitation for the historical storms at the ARW after a 6 degrees shift from N to S

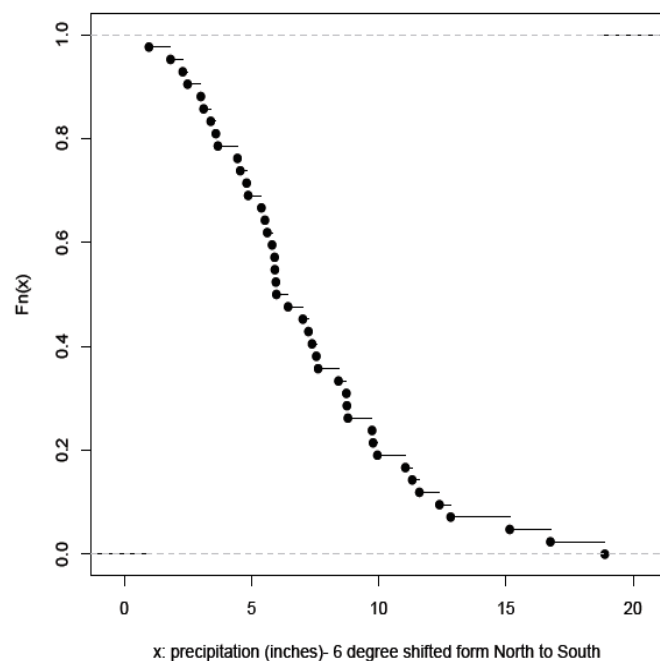


Figure 5.18 Exceedance probability distribution of 72-hr maximum basin averaged precipitation for historical storms at the ARW after a 6 degrees N to S shift

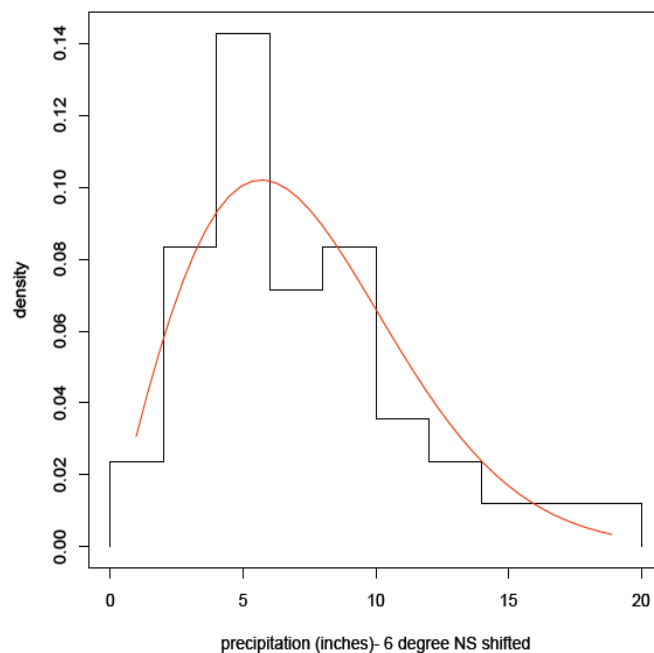


Figure 5.19 Weibull distribution fitted to the relative frequency histogram of 72-hr maximum basin averaged precipitation for the historical storms at the ARW after a 6 degrees N to S shift

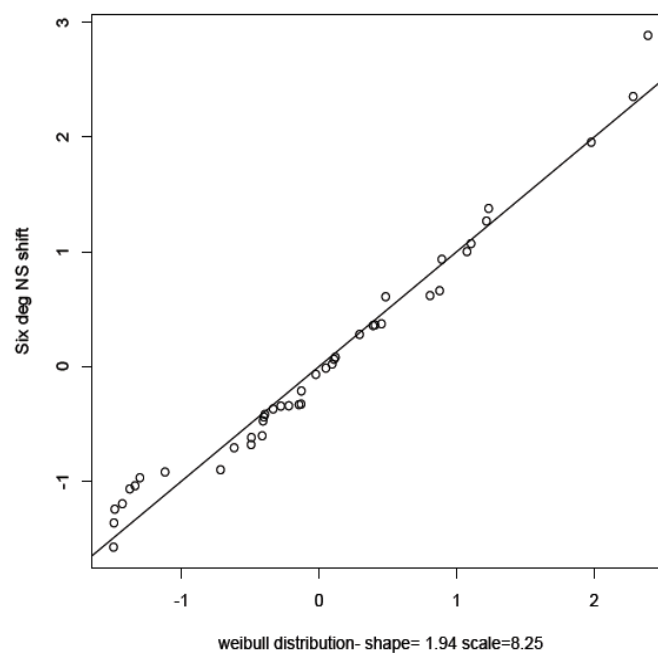


Figure 5.20 Q-Q plot for historical storms after a 6 degrees N to S shift

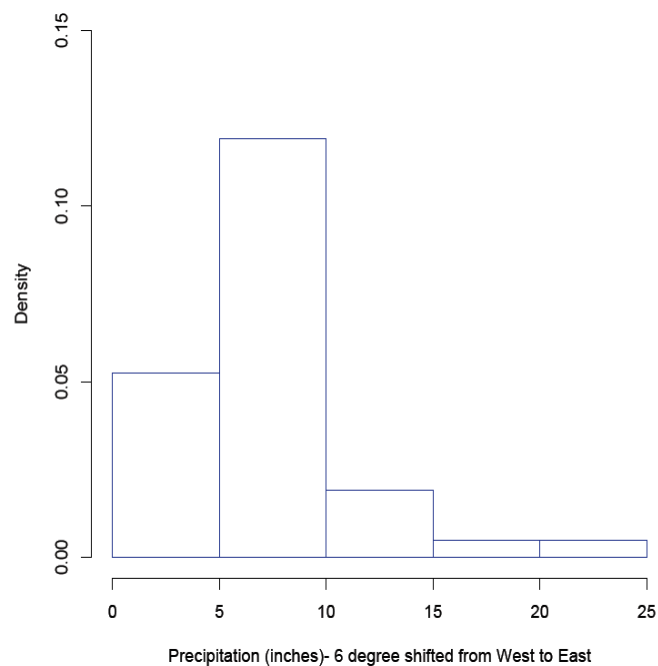


Figure 5.21 Relative frequency histogram of 72-hr maximum basin averaged precipitation for the historical storms at the ARW after a 6 degrees shift from W to E

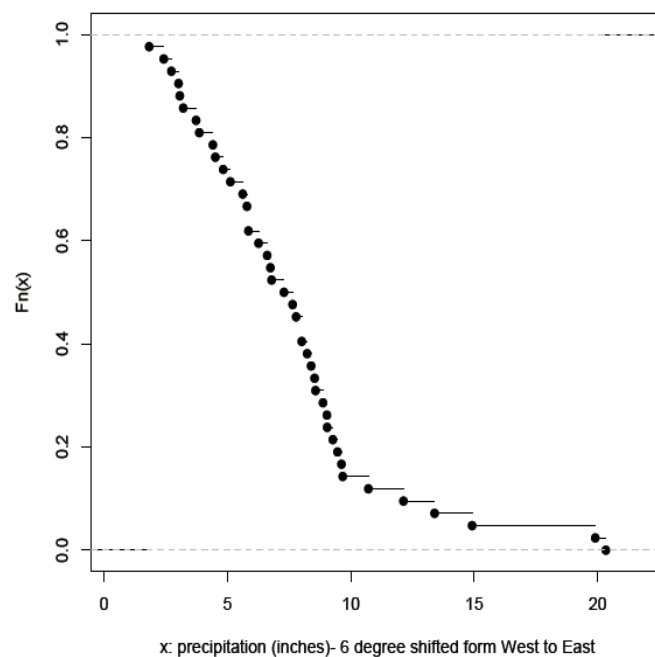


Figure 5.22 Exceedance probability distribution of 72-hr maximum basin averaged precipitation for historical storms at the ARW after a 6 degrees W to E shift

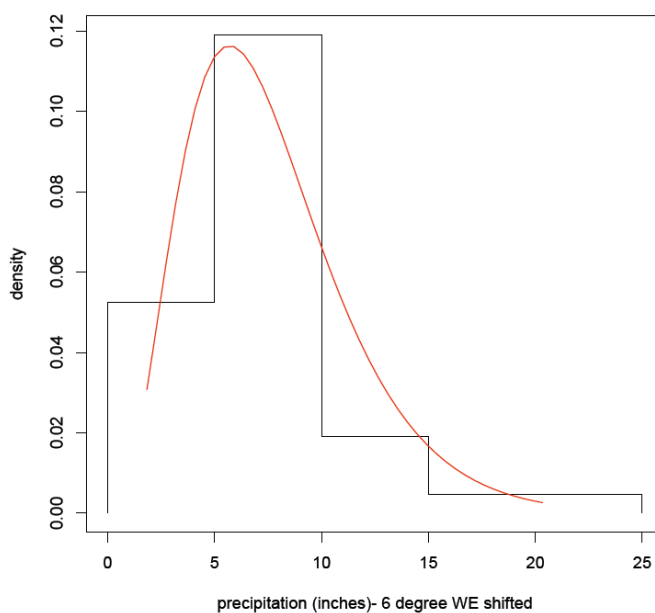


Figure 5.23 Gamma distribution fitted to the relative frequency histogram of 72-hr maximum basin averaged precipitation for the historical storms at the ARW after a 6 degrees W to E shift

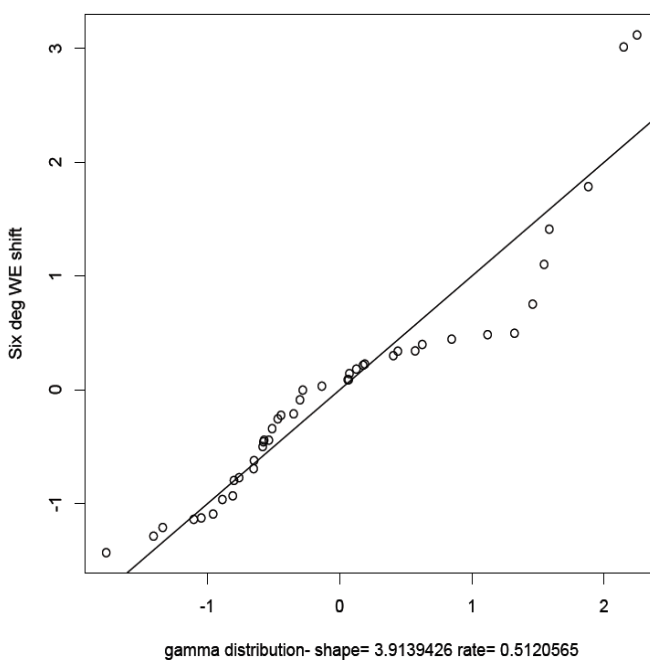


Figure 5.24 Q-Q plot for historical storms after a 6 degrees W to E shift

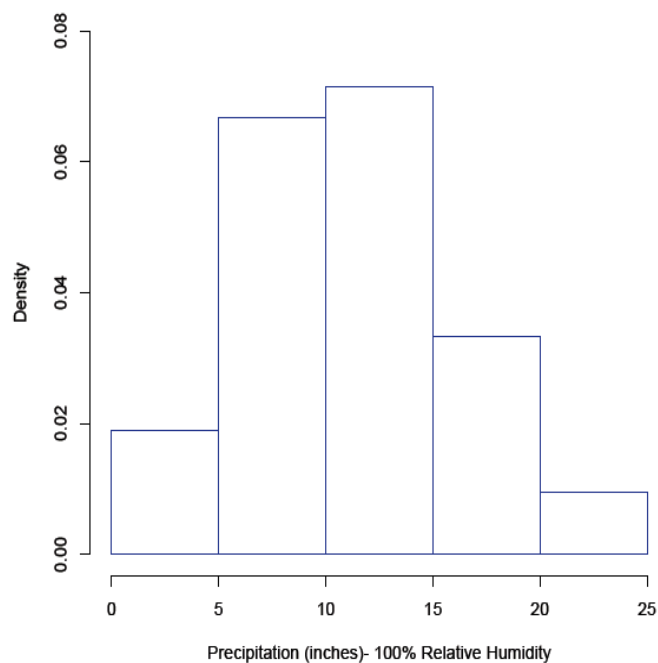


Figure 5.25 Relative frequency histogram of 72-hr maximum basin averaged precipitation for the historical storms at the ARW after a 100% relative humidity adjustment

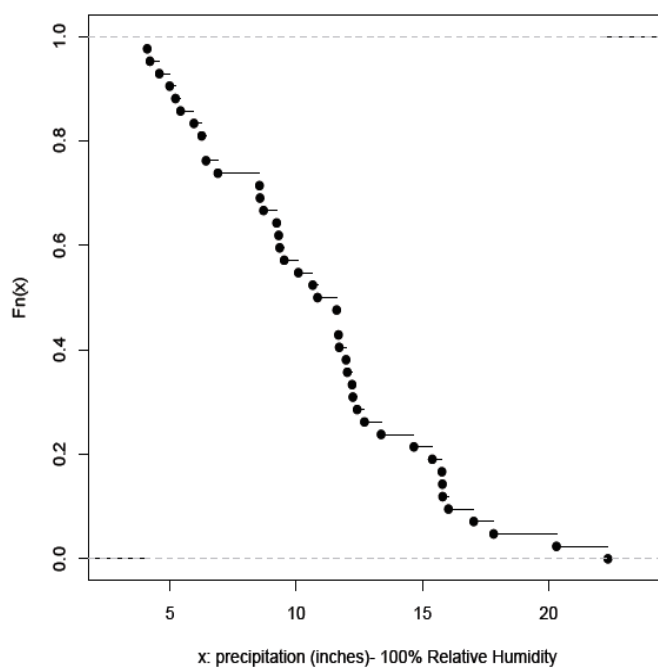


Figure 5.26 Exceedance probability distribution of 72-hr maximum basin averaged precipitation for historical storms at the ARW after a 100% RH adjustment

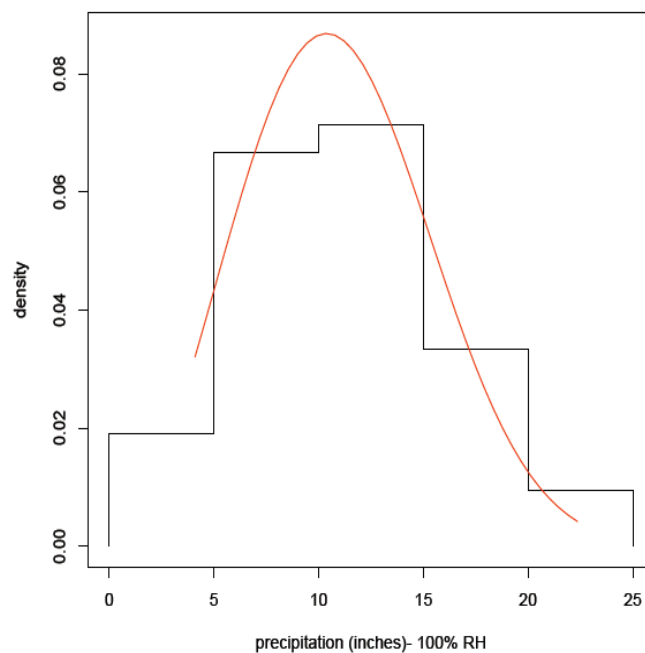


Figure 5.27 Weibull distribution fitted to the relative frequency histogram of 72-hr maximum basin averaged precipitation for the historical storms at the ARW after a 100% RH adjustment

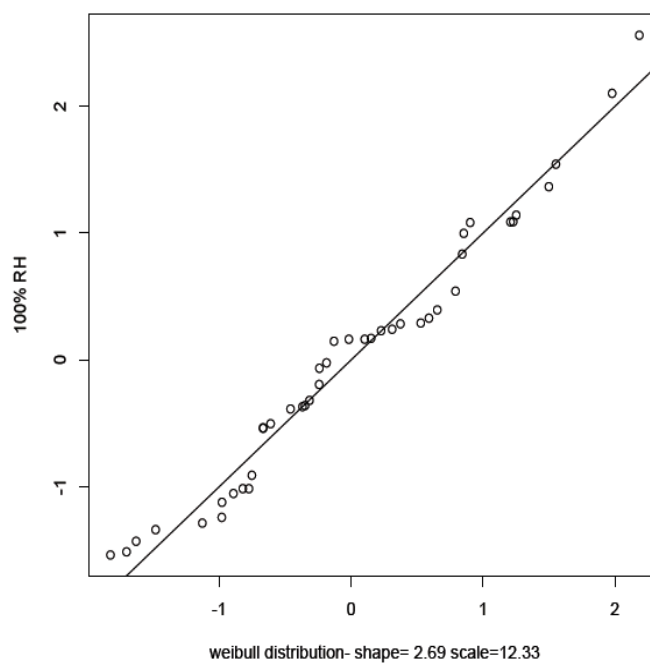


Figure 5.28 Q-Q plot from historical storms after a 100% RH adjustment

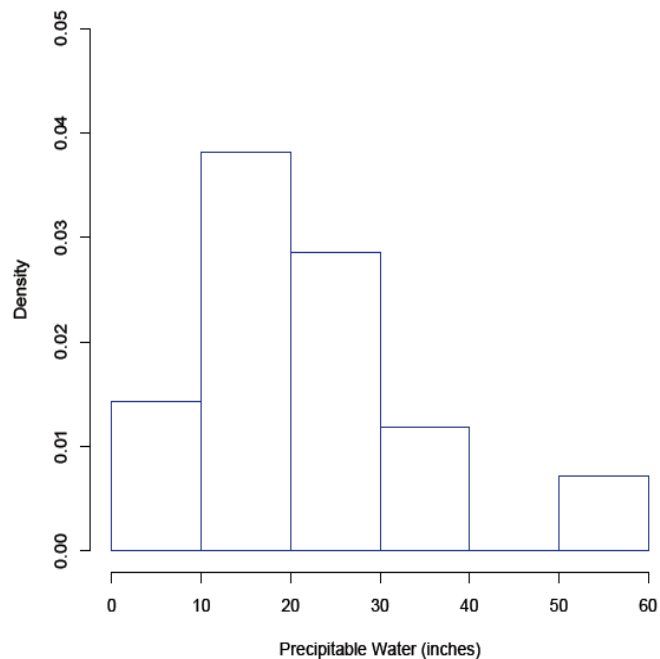


Figure 5.29 Relative frequency histogram of 72-hr maximum basin averaged precipitation for the historical storms at the ARW corresponding to the WRF model-calculated precipitable water

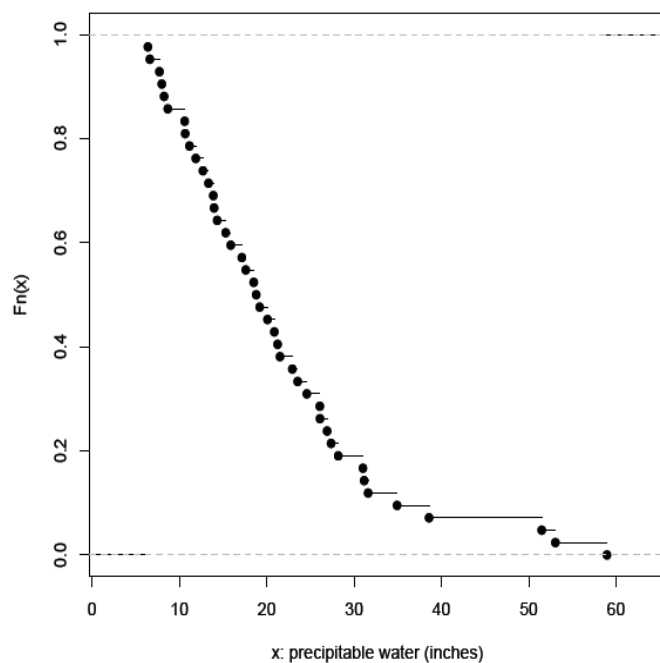


Figure 5.30 Exceedance probability distribution of 72-hr maximum basin averaged precipitation for historical storms at the ARW corresponding to the WRF model-calculated precipitable water

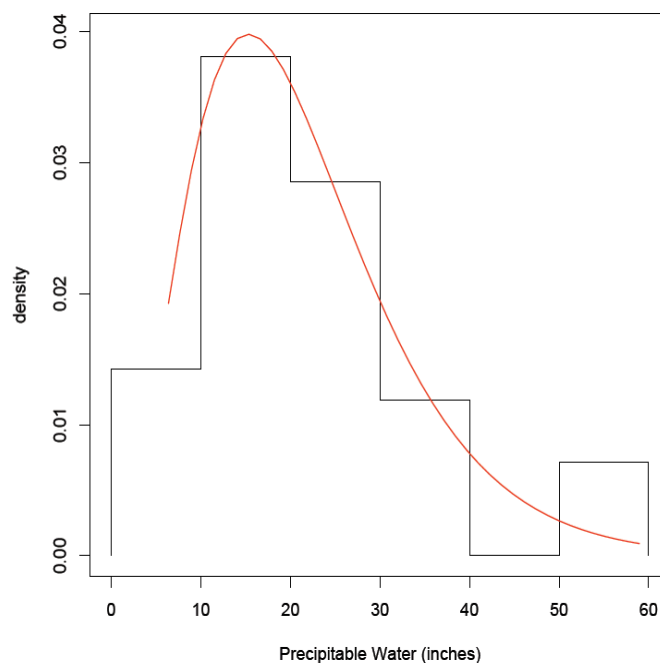


Figure 5.31 Gamma distribution fitted to the relative frequency histogram of 72-hr maximum basin averaged precipitation for the historical storms at the ARW corresponding to the WRF model-calculated precipitable water

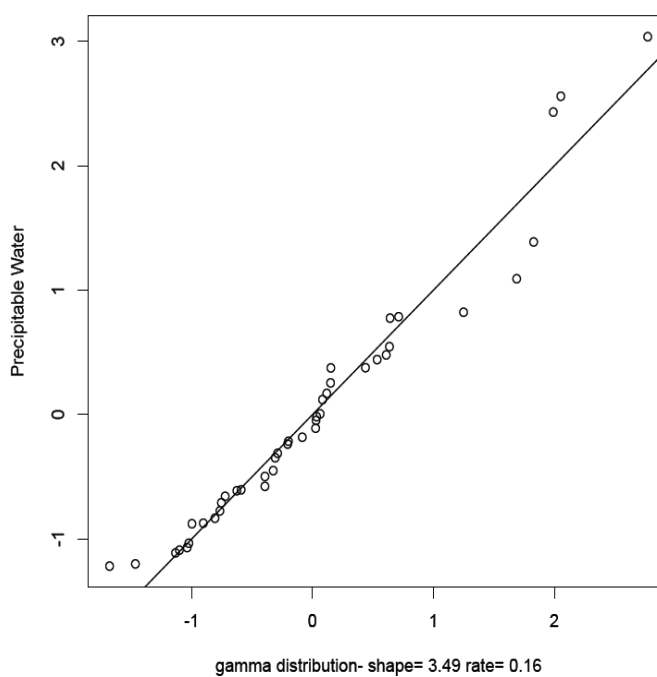


Figure 5.32 Q-Q plot from historical storms corresponding to precipitable water

Statistical analyses of historical maximum precipitation events and their maximization methods are presented from Figure 5.5 to Figure 5.32. The analyzed maximization methods are two-degree NS shift, four-degree NS shift, six-degree NS shift, six-degree WE shift, 100% relative humidity adjustment, and maximum precipitation corresponding to the WRF-model-estimated precipitable water. Therefore, 7 categories for historical maximum precipitation, including observed/modeled events, are investigated. Each category has four statistical analyses: 1. Relative frequency histogram of 72-hr maximum basin averaged precipitation for the historical storms at the ARW corresponding to each of the 7 categories (Figures 5.5, 5.9, 5.13, 5.17, 5.21, 5.25, and 5.29), 2. Exceedance Probability Distribution of 72-hr maximum basin averaged precipitation for historical storms at the ARW corresponding to each of the 7 categories (Figures 5.6, 5.10, 5.14, 5.18, 5.22, 5.26, and 5.30), 3. Theoretical probability distributions fitted to the above-mentioned relative frequency histograms (Figures 5.7, 5.11, 5.15, 5.19, 5.23, 5.27, and 5.31), and 4. Q-Q Plots (Figures 5.8, 5.12, 5.16, 5.20, 5.24, 5.28, and 5.32). Quantile-Quantile (Q-Q) plots are used to double check how well theoretical probability distributions fit to the relative frequency histograms. If all points in Q-Q plot lie on the line $y = x$, then it means that two distributions are match exactly. As it is seen from the figures mentioned above, Gamma and Weibull distributions provide a good approximation to the maximum precipitation data. All statistical analyses are performed using the statistical environment and language R.

The appropriate theoretical statistical distribution for the relative frequency histogram of each category, shown in Table 5.2, is calibrated for its parameters using the maximum-likelihood estimation first. Then the selected theoretical probability densities are plotted over their corresponding relative frequency histograms for visual inspection and their Q-Q plots are also prepared for evaluating the goodness of fit of the historical maximum precipitation

event data to the corresponding theoretical probability distributions. Results show that the modeled historical extreme precipitation events are fitted best by the gamma distribution (Figure 5.7).

Table 5.2 Statistical distributions and their parameters for historical events					
Precipitation Maximization Methods	Distribution	Maximum-likelihood Fitting			
		Shape	Standard Error	Rate Scale	Standard Error
Historical	Gamma	4.66	0.98	0.69	0.15
2° NS	Gamma	3.76	0.79	0.49	0.11
4° NS	Gamma	3.67	0.77	0.48	0.11
6° NS	Weibull	1.94	0.23	8.25	0.69
6° WE	Gamma	3.91	0.82	0.51	0.11
100% RH	Weibull	2.69	0.32	12.33	0.75
Precipitable Water	Gamma	3.49	0.73	0.16	0.04

Moreover, the statistical distributions of historically maximized events depend on the maximization methods. The distribution of 2-deg NS, 4-deg NS, and 6-deg WE shifting methods are fitted to a Gamma distribution as well as precipitable water maximization method. Meanwhile, the distribution of 6-deg NS shift and 100% RH maximization methods are fitted by Weibull distributions.

In reality, although the shifting of the systems is highly possible, it may not be possible to obtain maximum precipitation by 100% RH adjustment and or by the precipitable water approach. Therefore, it needs to be discussed how realistic these two maximization methods are. For this reason, the exceedance probability graphs of the ratios of historical precipitation to maximized precipitation by 100% RH adjustment method and precipitable water approach are plotted as shown in Figures 5.33 and 5.34.

It is hypothesized that “100% RH adjustment approach in precipitation maximization is acceptable if the exceedance probability of the ratio of historical precipitation, MP_{hist} , to precipitation from 100% RH adjustment, MP_{RH100} , is close to 1 at the significance level of 0.05.”

The exceedance probability graph of the ratio of historical precipitation to precipitation from %100 RH adjustment (Figure 5.33) shows that

$$P\left[\frac{MP_{hist}}{MP_{RH100}} > 0.8\right] \leq 0.05 \quad (5.3)$$

Therefore, the hypothesis is rejected, and it means that 100% RH adjustment approach in precipitation maximization over the ARW is not physically possible.

It is also hypothesized that “Precipitable Water approach in precipitation maximization is acceptable if the exceedance probability of the ratio of historical precipitation, MP_{hist} , to precipitable water, PW_r , is close to 1 at the significance level of 0.05.”

The exceedance probability graph of the ratio of historical precipitation to precipitable water (Figure 5.34) shows that

$$P\left[\frac{MP_{hist}}{PW_r} > 0.5\right] \leq 0.05 \quad (5.4)$$

Therefore, the hypothesis is also rejected, and it means that the precipitable water approach in precipitation maximization over the ARW is not physically possible.

As a result, PW and 100% RH methods are eliminated from further consideration.

The following equations are based on *Guttman et al* [1982]. “Reliability is defined as the probability that a system performs properly, for the period of time intended, under acceptable operating conditions” [*Guttman et al*, 1982]. In this study, therefore, the probability of the maximum precipitation occurrence is going to be defined as reliability.

Letting r represent the random variable equal to the probable maximum precipitation that can possibly occur, which is 20.33 inches based on accepted maximization methods, $f(r)$ can be assumed its probability density function. Then the reliability $R(r)$ can be defined for $r = PMP$ as,

$$R(r) = 1 - F(r) \quad (5.5)$$

where the cumulative distribution function is defined as,

$$F(r) = \int_0^r f(x) dx \quad (5.6)$$

$R(r)$ can also be called as exceedance probability, as it is used previously, and/or complementary cumulative distribution function.

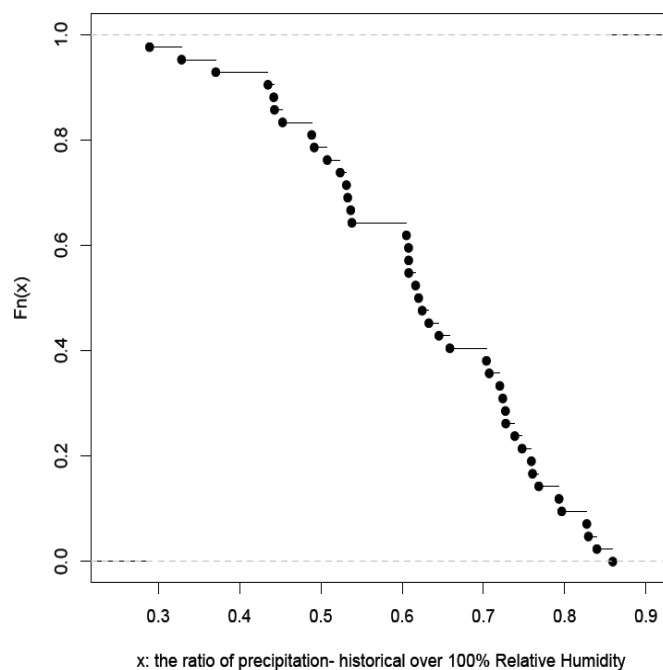


Figure 5.33 Exceedance probability of the precipitation ratio-historical over 100% RH

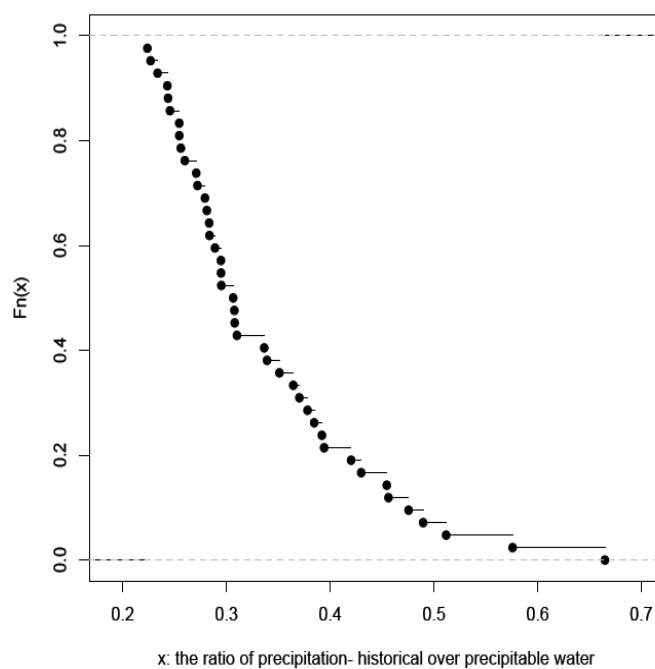


Figure 5.34 Exceedance probability of the precipitation ratio-historical over PW

As presented in Table 5.2, the statistical distributions of the accepted maximization methods satisfy both Gamma and Weibull distributions. Probability density function of Gamma distribution is defined as,

$$f(r|\gamma, \lambda) = \frac{\lambda^\gamma}{\Gamma(\gamma)} r^{\gamma-1} e^{-\lambda r}, \quad r \geq 0, \gamma > 0, \lambda > 0 \quad (5.7)$$

where γ and λ are shape and rate parameters, respectively, and $\Gamma(\gamma)$ is defined as,

$$\Gamma(\gamma) = \int_0^\infty x^{\gamma-1} \exp(-x) dx, \quad \gamma > 0 \quad (5.8)$$

Probability density function of Weibull distribution, on the other hand, is defined as,

$$f(r|\alpha, \beta) = \frac{\beta}{\alpha} \left(\frac{r}{\alpha} \right)^{\beta-1} e^{-(r/\alpha)^\beta} \quad (5.9)$$

where β and α are shape and scale parameters, respectively.

As a result, exceedance probability distributions of accepted precipitation maximization methods of this study and modeled historical events are computed integrating the equations 5.5 and 5.7 via R with the parameters presented in Table 5.2. The resultant distributions are illustrated in the following Figures 5.35 and 5.36.

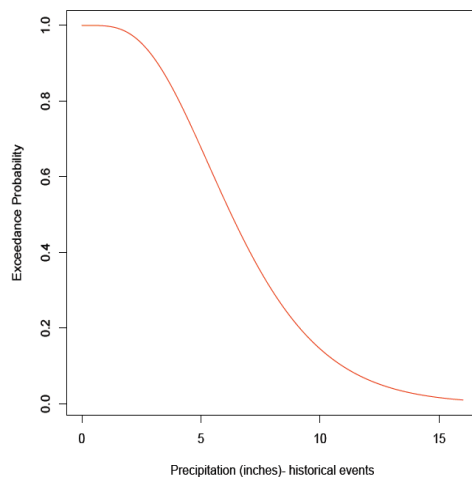


Figure 5.35 Exceedance probability of 72-hr maximum basin averaged precipitation for the historical storms at the ARW

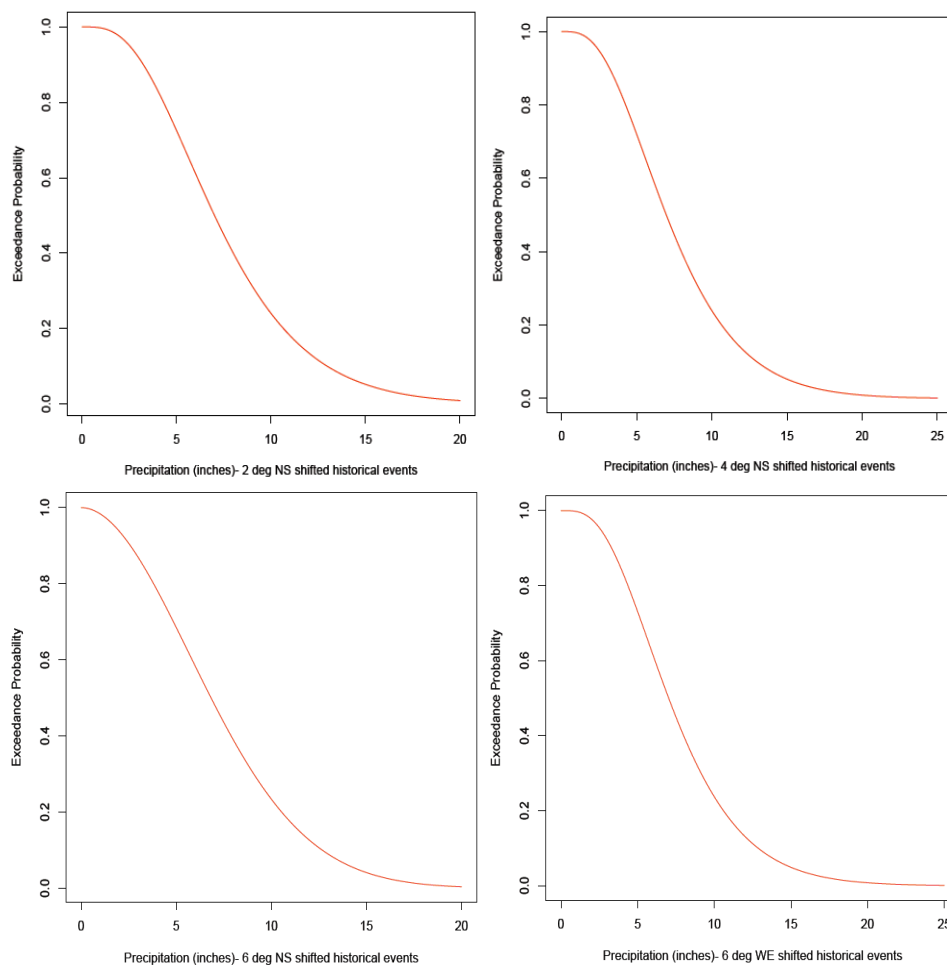


Figure 5.36 Exceedance probabilities of maximized historical events

Based on the exceedance probability distributions shown in Figures 5.39 and 5.40, precipitation values of historical storms can be tabulated for various degrees of exceedance probability and for precipitation maximization methods as shown in Table 5.4.

Exceedance Probability(%)	Historical	2° NS	4° NS	6° NS	6° WE
0.5	17.467	21.588	21.722	19.486	21.232
1	16.060	19.715	19.822	18.127	19.414
2	14.606	17.787	17.867	16.665	17.542
5	12.584	15.122	15.167	14.524	14.951
10	10.944	12.979	12.997	12.681	12.864
25	8.522	9.850	9.834	9.763	9.811
37	7.325	8.325	8.294	8.226	8.318
50	6.277	7.005	6.964	6.830	7.024
60	5.549	6.098	6.051	5.836	6.132
70	4.835	5.220	5.168	4.849	5.267
75	4.468	4.773	4.719	4.341	4.826
80	4.083	4.307	4.253	3.808	4.366
85	3.664	3.806	3.751	3.234	3.870
90	3.181	3.236	3.181	2.586	3.304
95	2.550	2.508	2.454	1.785	2.577
98	1.955	1.840	1.791	1.104	1.908
99	1.620	1.476	1.431	0.770	1.540
99.5	1.353	1.193	1.152	0.538	1.253

As a result of this research, 72-hr basin averaged probable maximum precipitation with a an exceedance probability of 0.5 percent is 21.722 inches for the American River Watershed. This result can also be assumed as the physically possible upper bound of the probable maximum precipitation.

Chapter VI

Summary and Conclusions

The determination of the optimum probable maximum precipitation (PMP) is needed for design purposes to meet safety standards in the construction of highly efficient and less costly structures. For instance, this practice is crucial for the potential hazards associated with overtopping of large dams. Unfortunately, the current PMP methods do not meet these requirements.

The main motivation of this dissertation was to fulfill these needs. Accordingly, a new physically based methodology was developed for probable maximum precipitation estimation at the American River Watershed using a numerical weather prediction model. The methodology is mainly based upon a searching mechanism that tracks physically possible atmospheric conditions, which can cause maximum precipitation over the interested basin.

In this dissertation, it is proposed that numerical weather prediction models must be used in the estimation of PMP. Accordingly, the next generation Weather and Research Forecasting Model (WRF) was chosen for the development of the new estimation methodology. Calibration and validation results, based on 42-historical storm events, regarding both areally-averaged and local precipitation, show that the WRF model is reliable for PMP studies. As a result of the calibration and validation study, Thompson microphysics-Grell 3D ensemble cumulus-YSU boundary layer physics triplet was chosen as the best modeling options for the American River Watershed under the consideration of both the precipitation intensity and timing. This conclusion is also supported by the performed sensitivity analyses.

The steps for the proposed methodology for PMP determination are as follows:

1. Determination of persistent atmospheric systems, which cause maximum precipitation at the domain of interest.
2. Gathering a sufficient number of historical maximum precipitation events for the specified domain in order to be able to make reliable statistical inferences.
3. Modeling of the most severe historical hydro-climate event for calibration purposes of the model physics.
4. Modeling of all historical severe hydro-climate events with the calibrated physics options in order to validate the model physics.
5. Application of sensitivity analyses as a control mechanism for the validation and calibration procedures.
6. Determination of maximization methods. Four precipitation maximization approaches are proposed: i. Perturbation, ii. Shifting, iii. Replacement, and iv. Worst case scenario creation.
7. Numerical modeling of each of the maximization approaches in order to evaluate the behavior of maximum precipitation over the domain of interest.
8. Determination of the worst-case scenario method in order to determine the upper limit of the maximum precipitation.
9. Assessment of the climate change effect on precipitation intensity over the domain/basin of interest as a control mechanism for the worst-case scenario.

10. Modeling of all historical cases based on the physically possible methods.
11. Elimination of the methods that cannot be physically possible using statistical tools.
12. Determination of PMP based on the exceedance probabilities of the physically possible maximization methods.

Contrary to the common belief that numerical weather prediction models cannot be used in practice for the determination of probable maximum precipitation, although they are believed to be helpful in a limited way, in this dissertation it is shown that the PMP procedures, based on the developed estimation methods, can be used in practice.

The most significant limitation of the traditional method is related to the recognition of the effects of mesoscale systems, which play crucial role in precipitation production locally. Most of the PMP calculation attempts disregard this effect. All the previous traditional maximization procedures have been performed locally with little physical basis about the possibility of their occurrences. For instance, local moisture maximization would have equivalent impact with simulating a hurricane over California. This physical bound can only be determined by using weather forecast models.

The results of traditional PMP method are not consistent with the results of this study. In *HMR36*, 72hr basin averaged PMP for the American River Watershed is estimated as 31.48 inches, whereas PMP is determined as 28.57 inches in the next version *HMR59*. These two numbers are significantly higher than 21.722 inches, which is found in this research.

For comparison purposes, the traditional PMP values (inches) for historical events are presented in Table 6.1. It is seen in this table that only 6 PMP values for historical events are available from the traditional PMP method. All these 6 PMP values are linearly interpolated

to 1861 square mile storm area for the American River Watershed.

Table 6.1 Physically possible maximum precipitation comparisons with traditional PMP obtained from HMR59 (inches)

Water Year	Month	Day	Year	Origin	2° N	4° N	6° N	6° W	Traditional
1951	11	20	1950	10.29	8.81	7.27	4.56	9.67	16.89
1956	12	23	1955	13.08	15.27	15.71	16.75	19.90	18.95
1963I	10	13	1962	13.78	17.37	13.79	9.95	10.71	23.06
1963II	2	1	1963	9.59	10.33	10.54	11.32	8.39	N/A
1965	12	23	1964	15.00	19.90	21.16	18.89	20.33	18.84
1966	11	18	1965	3.08	3.90	2.73	3.68	2.42	N/A
1967	1	22	1967	7.72	9.65	7.72	8.75	8.01	N/A
1968	2	21	1968	4.29	6.27	9.17	9.78	9.46	N/A
1969	1	21	1969	5.85	13.49	7.65	3.12	5.85	16.02
1970	1	16	1970	4.14	4.34	6.48	5.92	7.78	N/A
1971	12	3	1970	6.15	8.85	8.96	7.38	7.64	N/A
1972	12	24	1971	3.95	4.09	5.74	7.62	5.85	N/A
1973	1	18	1973	6.22	6.11	5.52	5.39	5.62	N/A
1974	11	12	1973	7.39	7.95	8.65	12.39	5.12	N/A
1975	2	3	1975	7.08	6.43	5.98	4.87	4.51	N/A
1976	10	27	1975	2.02	4.20	5.85	5.98	3.07	N/A
1977	1	3	1977	2.71	3.54	3.15	2.30	1.83	N/A
1978	1	16	1978	7.10	6.29	4.42	3.01	6.74	N/A
1979	1	12	1979	4.73	5.01	5.95	5.53	8.01	N/A
1980	1	13	1980	8.06	9.49	10.70	11.60	8.53	N/A
1981	1	29	1981	6.52	5.13	4.07	3.60	3.02	N/A
1982	2	15	1982	8.88	10.40	12.01	12.83	14.91	N/A
1983	12	22	1982	7.29	7.35	7.50	7.55	6.79	N/A
1984	12	26	1983	7.99	6.86	4.84	3.40	9.62	N/A
1985	2	10	1985	5.39	5.22	5.17	4.81	3.86	N/A
1986	2	18	1986	12.54	12.93	12.53	9.74	12.13	20.36
1987	2	13	1987	3.26	4.47	5.56	5.81	6.26	N/A
1988	4	21	1988	3.11	1.78	1.64	1.82	5.79	N/A
1989	11	25	1988	6.76	8.29	8.63	8.73	9.04	N/A
1990	11	26	1989	2.68	3.34	3.79	4.45	3.21	N/A
1991	3	3	1991	7.21	7.48	7.02	7.02	8.87	N/A
1992	2	16	1992	3.79	2.32	2.34	2.49	3.73	N/A
1993	12	11	1992	5.41	6.26	8.16	7.24	9.27	N/A
1994	2	20	1994	3.94	3.18	3.65	5.96	4.41	N/A
1995	3	12	1995	9.80	10.59	9.66	8.79	7.29	N/A
1996	12	13	1995	7.10	10.18	13.10	11.05	8.23	N/A
1997	1	3	1997	11.48	15.76	17.01	15.15	13.39	N/A
1998	1	13	1998	4.36	5.64	5.79	6.44	6.61	N/A
1999	2	9	1999	9.15	8.07	7.74	8.42	9.03	N/A
2000	2	14	2000	7.14	8.66	7.14	5.62	8.57	N/A
2001	2	12	2001	3.80	3.16	2.20	0.97	2.73	N/A
2002	12	3	2001	4.30	5.40	6.37	5.91	4.83	N/A

For example, according to the traditional method, for the 1986 historical flood event, the estimated PMP is 20.18 inches for the 72-hr duration and for a 2,000 square miles storm area [HMR59]. The PMP for the same duration is estimated as 21.50 inches for 1,000 square miles storm area. The ARW is 1860 square miles and it is assumed that the 1986 storm covers the whole watershed. Therefore, the traditional PMP estimation is linearly interpolated to 20.36 inches for the ARW as shown in Table 6.1.

The comparisons of our proposed maximization methods, modeled historical events and traditional method, shown in Table 6.1, indicates that the traditional PMP method overestimates PMPs based on 1951, 1956, 1963I, 1969, and 1986 events. It underestimates the PMP for the 1965 case. On the other hand, it is found in this study that the overall probable maximum precipitation obtained from the analyses of 42 historical storm events is 21.722 inches. According to *HMR59*, the overall PMP is 28.57 inches for AR Basin. This value is even higher than the highest traditional PMP amount based on 1963I case (Table 6.1). The reason of this contradiction is unknown.

On the other hand, the current operational PMP estimation for the American River Watershed is 28.57 inches as published in the *HMR59* and a previous PMP value was 31.48 inches as published in the *HMR36*. According to the exceedance probability analyses of this proposed method, the reliabilities of these two estimations are 0.036 percent and 0.011 percent, respectively.

Therefore, it is concluded that overall the traditional PMP methods estimate higher probable maximum precipitation than that of the method of this study for the American River Watershed.

Although most of this study was performed for 72-hr basin-averaged maximum precipitation values for comparison purposes, it may be inferred that the developed method can be applied to any location without any assumption on the spatial distribution of precipitation.

Furthermore, the developed PMP estimation approach can be used in any geographical region, while the traditional PMP is inapplicable in tropics, for instance, due to the weak relations between dew point temperatures and precipitation.

The validation results of this study show that one of the most challenging problems of the traditional PMP estimation, the accounting of the orography effect on precipitation, is no longer an issue with the new method, since the numerical atmospheric model WRF solves atmospheric dynamics with respect to terrain following coordinates.

Here an update in the PMP definition that is more consistent with the newly developed PMP estimation method, is proposed. First of all, “Maximum Possible Precipitation” term had been used before the “Probable Maximum Precipitation” term was proposed. It was found to be too deterministic when the uncertainties and limitations of the method are considered. That is why its name was changed to PMP [Weisner, 1970]. Here, it is claimed that these uncertainties are reduced by means of numerical atmospheric modeling approach, so that the older term “*Maximum Possible Precipitation*” may be used, as was suggested by Prof. Carlos Puente [Author’s *QE*, 2007]. Another alternative name to consider may be “*Possible Extreme Precipitation*.”

6.1 Future Perspectives

The first following effort of this dissertation would be related to the determination of PMP based on the storm durations. The traditional PMP methods assume that PMP increases linearly with time that needs to be evaluated with our new method in detail. In this research, on the other hand, the PMP intensities are evaluated for a fixed period of time for comparison purposes. It is known from this research that 72 hr can be reached for extreme events. The different storm durations could not be analyzed in this study since a historical extreme precipitation realization that covers a longer period of time was needed than the 72 hr standard design duration that was addressed in this research. In other words, since the events would additionally need to be clustered in terms of duration, the total number of events for each cluster would not be adequate in order to make any statistical inference for this work.

Once the duration effect is included to the determination of PMP then the traditional definition can be reduced to “The theoretical greatest depth of precipitation.”

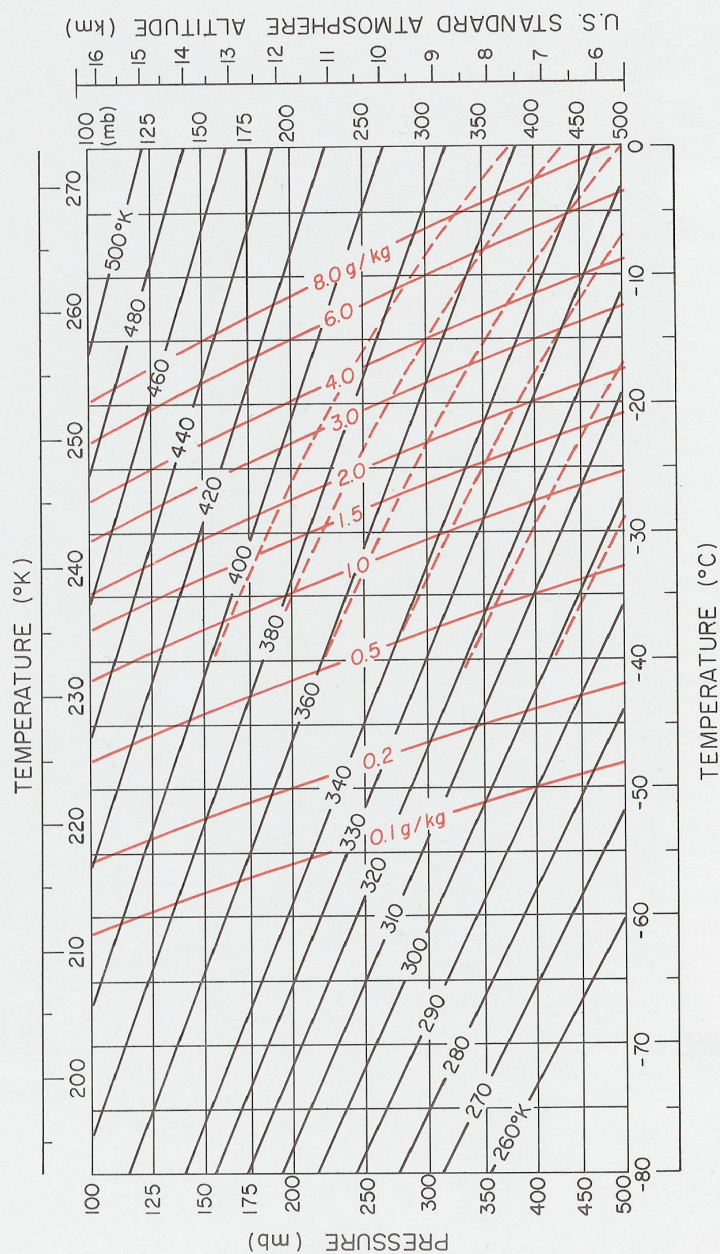
Subsequently, climate change effect on extreme precipitation can be investigated further in terms of both intensity and frequency.

Finally, the proposed method can be applied to the traditional probable maximum flood estimations, and it can further be used for the determination of *possible extreme floods*, as being analogous to this study.

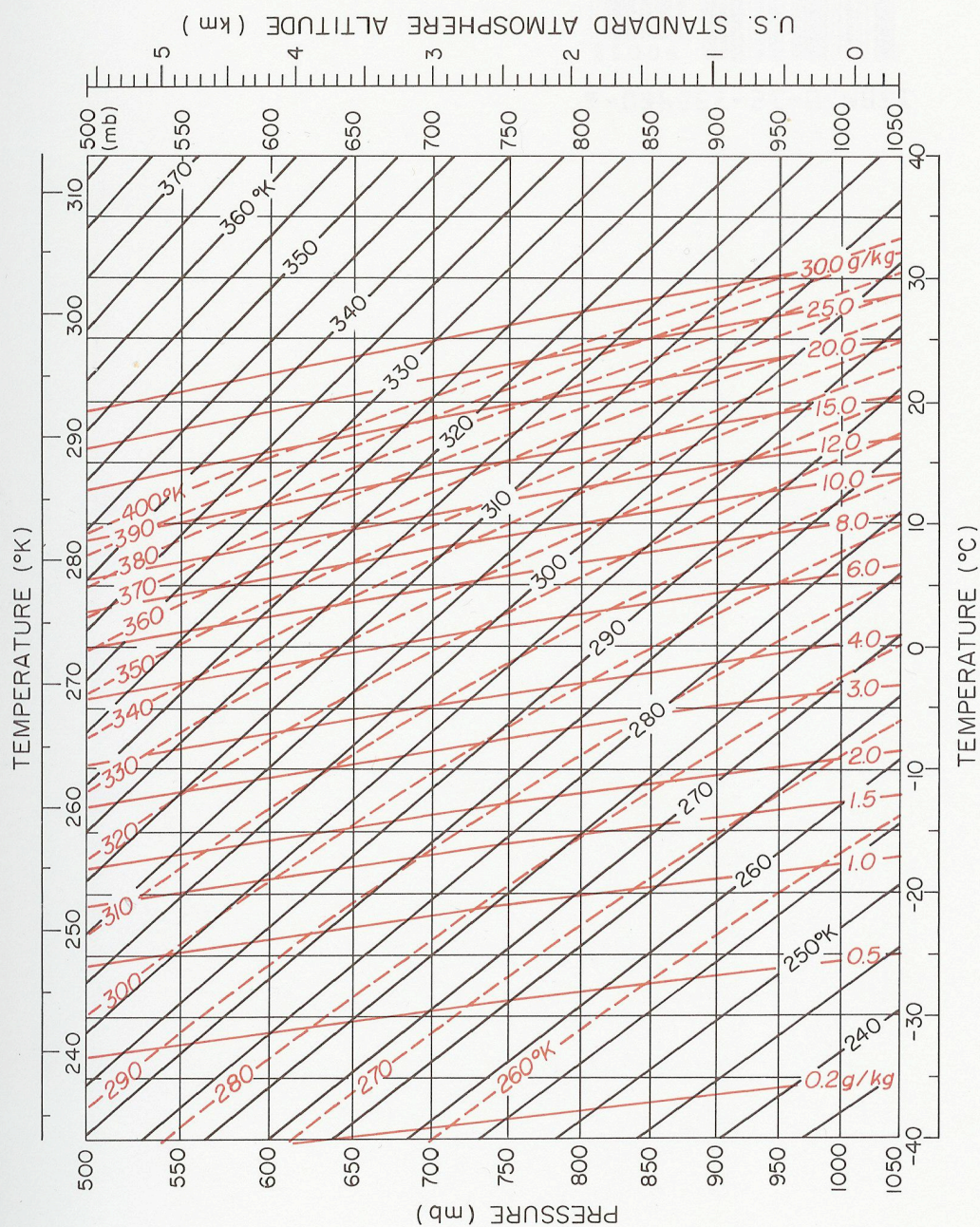
Appendix I

The Pseudoadiabatic Chart [Wallace and Hobbs, 1977]

The pseudoadiabatic chart Black sloping lines denote *dry adiabats* which are lines of constant potential temperature θ labeled in degrees Kelvin. Red solid lines refer to saturation mixing ratio w_s labeled in grams of water vapor per kilogram of dry air. Dashed red lines denote *pseudoadiabats*, which are lines of constant equivalent potential temperature θ_e for saturated air, labeled in degrees Kelvin. The ordinate scale is linearly proportional to p^{R_d/c_p} . The altitude scale at the right is for the U.S. Standard Atmosphere. See text for further explanation.



The Pseudoadiabatic Chart [Wallace and Hobbs, 1977]-continued



Bibliography

- Abbs, D.J., 1999: A numerical modeling study to investigate the assumptions used in the calculation of probable maximum precipitation. *Water Resources Research*, **35**(3), 785-796.
- American Meteorological Society, 1959: Glossary of Meteorology. Boston, Massachusetts, 446 pp.
- Arakawa, A., 1997: Adjustment mechanisms in atmospheric models. *Journal of the Meteorological Society of Japan*, **75**(1B), 155-179.
- Arakawa, A. and V.R. Lamb, 1977: Computational design of the basic dynamical process of the UCLA general circulation model. *Methods in Comp. Physics*, **17**, 173-265.
- Asai, T., 1965: A numerical study of air-mass transformation over the Japan sea in winter. *J. Meteor. Soc. Japan*, **43**, 1-15.
- Baker, D., and Estes, G., 1994: Using the TERC Weather pattern to predict heavy rainfall in California. *Predicting Rainfall Events in California: A Symposium to Share Weather Pattern Knowledge*, Rocklin, California.
- Banacos, P.C., and D.M. Schultz, 2005: The use of moisture flux convergence in forecasting convective initiation: Historical and operational perspectives. *Wea. Forecasting*, **20**, 351-366.
- Barnett, T., R. Malone, W. Pennell, D. Stammer, A. Semtner, and W. Washington, 2004: The effects of climate change on water resources in the west: Introduction and Overview. *Climatic Change*, **62**, 1-11.
- Betts, A.K., 1986: A new convective adjustment scheme. Part I: Observational and theoretical basis. *Quart. J. Roy. Meteor. Soc.*, **112**, 677-691.
- Betts, A.K., and M.J. Miller, 1986: A new convective adjustment scheme. Part II: Single column tests using GATE wave, BOMEX, and arctic air-mass data sets. *Quart. J. Roy. Meteor. Soc.*, **112**, 693-709.
- Blackadar, A.K., 1976: Modeling the nocturnal boundary layer. *Preprints of the Third Symposium on Atmospheric Turbulence and Air Quality*, Rayleigh, NC, 19-22 October 1976, Amer. Meteor. Soc., Boston, 46-49.
- Blackadar, A.K., 1978: Modeling pollutant transfer during daytime convection. *Preprints, Fourth Symp. on Atmospheric Turbulence, Diffusion, and Air Quality*, Reno, NV, Amer. Meteor. Soc., 443-447.
- Bohren, C.F., and B.A. Albrecht, 1998: *Atmospheric Thermodynamics*. Oxford Oxfordshire: Oxford University Press.
- Bond, N.A., and G.A. Vecchi, 2003: The Influence of the Madden-Julian Oscillation on Precipitation in Oregon and Washington, *Weather and Forecasting*, **18**, pp. 600-613.

Campos-Aranda, D.F., 1998: Statistical estimate of PMP in San Luis Potosi, Mexico, *Ingenieria Hidraulica En Mexico*, **13**(3), 45-66.

Casas, M.C., R. Rodriguez, R. Nieto, and A. Redano, 2008: The Estimation of Probable Maximum Precipitation the Case of Catalonia. *Trends And Directions In Climate Research*, **1146**, 291-302.

Cayan, D.R. and K.T. Redmond, 1994: ENSO Influences on Atmospheric Circulation and Precipitation in the Western United States. Technical Report 36, California Department of Water Resources, Interagency Ecological Studies Program.

Cayan D.R., and D.H. Peterson, 1989: The influence of the North Pacific circulation on streamflow in the West. *Aspects of Climate Variability in the Pacific and Western Americas, Geophys. Monogr.*, No. 55, Amer. Geophys. Union, 375–397.

Cayan, D.R., K.T. Redmond, and L.G., Riddle, 1999: ENSO and hydrologic extremes in the western United States. *J. Climate*, **12**, 2881-2893.

Chen, L.C., 2005: An Investigation of the Moisture Maximization for the Probable Maximum Precipitation, Dissertation, University of Iowa, 195 pp.

Chen, L.C., and A.A. Bradley, 2006: Adequacy of Using Surface Humidity to Estimate Atmospheric Moisture Availability for Probable Maximum Precipitation. *Water Resources Research*, **42**(9), W09410, doi:10.1029/2005WR004469.

Chen, L.C., and A.A. Bradley, 2007: How Does The Record July 1996 Illinois Rainstorm Affect Probable Maximum Precipitation Estimates?. *Journal of Hydrologic Engineering*, **12**(3), 327-335.

Clark, C., 2002: Rainfall Estimates In Great Britain. *International Water Power & Dam Construction*, **54**(5), 18-26.

Clark, C., 2003: Estimating Areal Rainfall During the 1898 Flood in the English Lake District and the Implications for Probable Maximum Precipitation. *Weather*, **58**(10), 395-406.

Clark, C., and P.R. Rakhecha, 2002: Areal PMP Distribution of One-Day to Three-Day Duration over India. *Meteorological Applications*, **9**(4), 399-406.

Clark, R.A., 1967: Determination of Probable Maximum Precipitation Values in Tropical Regions. *Bulletin of the American Meteorological Society*, **48**(8), 639-&.

Codell, R.B., 1986: Runoff From Armored Slopes. Geotechnical and Geohydrological Aspects of Waste Management. *Proceedings of the 8th Annual Symposium|Geotechnical and Geohydrological Aspects of Waste Management. Proceedings of the 8th Annual Symposium*, 111-120|X +558.

Corps of Engineers, U.S. Army, 1945: Storm Rainfall in the United States.

Corrigan, P., D.D. Fenn, D.R. Kluck, and J.L. Vogel, 1998: Hydrometeorological Report No. 58, Probable Maximum Precipitation For California- Calculation Procedures, National Weather Service, 105 pp.

Corrigan, P., D.D. Fenn, D.R. Kluck, and J.L. Vogel, 1999: Hydrometeorological Report No. 59, Probable Maximum Precipitation for California, National Weather Service, 105 pp.

Cotton, W.R., R.L. McAnelly, C.T. Ashby, 2002: Simulations of Extreme Precipitation Events in the Colorado Rocky Mountains, *10th Conference on Mountain Meteorology and the Mesoscale Alpine Programme (MAP) Meeting 2002, 17-21 June*, Park City, UT.

Dawdy, D.R. and D.P. Lettenmaier, 1987: Initiative for risk-based flood design. *J. Hydraul. Eng.*, **113**(8):1041-1051.

Deardorff, J.W., 1972: Numerical investigation of neutral and unstable planetary boundary layers. *J. Atmos. Sci.*, **29**, 91–115.

Deardorff, J.W., 1978: Efficient prediction of ground surface temperature and moisture, with inclusion of a layer of vegetation. *J. Geophys. Res.*, **83**, 1889-1903.

Desa, M.N. and P.R. Rakhecha, 2007: Probable Maximum Precipitation for 24-hr Duration over an Equatorial Region: Part 2-Johor, Malaysia. *Atmospheric Research*, **84**(1), 84-90.

Dettinger, M.D., D.R. Cayan, H.F. Diaz, and D.M. Meko, 1998: North–south precipitation patterns in western North America on interannual-to-decadal timescales. *J. Climate*, **11**, 3095–3111.

Dhar, O.N. and P.P. Kamte, 1969: A Pilot Study for the Estimation of Probable Maximum Precipitation Using Hershfield Technique, *Indian Journal of Meteorology and Geophysics* | *Indian Journal of Meteorology And Geophysics*, **20**(1), 31-34.

Dhar, O.N. and P.P. Kamte, 1971: Estimation of Extreme Rainfall over North India, *Indian Journal of Meteorology and Geophysics* | *Indian Journal of Meteorology and Geophysics*, **22**(4), 559-566.

Dhar, O.N., and S. Nandargi, 1993a: Envelope Depth-Area-Duration Raindepths for Different Homogeneous Rainstorm Zones of The Indian Region. *Theoretical and Applied Climatology*, **47**(2), 117-125.

Dhar, O.N. and S. Nandargi, 1993b: The Zones of Severe Rainstorm Activity over India, *International Journal of Climatology*, **13**(3), 301-311.

Dhar, O.N., A.K. Kulkarni, and P.R. Rakhecha, 1981: Probable Maximum Point Rainfall Estimation for the Southern Half of the Indian Peninsula. *Proceedings of the Indian Academy of Sciences-Earth and Planetary Sciences*, **90**(1), 39-46.

Dhar, O.N., P.R. Rakhecha, B.N. Mandal, and R.B. Sangam, 1982: Was the July 1981 Rainstorm over Rajasthan Unprecedented. *Pure and Applied Geophysics*, **120**(3), 483-494.

Ding, Y., B. Zhang, and X. Fu, 1986: The Preliminary Study of the Moisture Field of a Depression over the Bay of Bengal During 1979 Summer Monex, *Scientia Atmospherica Sinica*|*Scientia Atmospherica Sinica*, **10**(1), 89-96.

Dole, R.M., and N.D. Gordon, 1983: Persistent anomalies of the extratropical Northern Hemisphere wintertime circulation; geographical distribution and regional persistence characteristics. *Mon. Wea. Rev.*, **111**, 1567-1586.

Douglas, E.M., and A.P. Barros, 2003: Probable Maximum Precipitation Estimation Using Multifractals: Application in the Eastern United States. *Journal of Hydrometeorology*, **4**(6), 1012-1024.

Douglas, E.M., and A.P. Barros, 2004: Probable Maximum Precipitation Estimation Using Multifractals: Application in the Eastern United States (Vol 4, Pg 1012, Yr, 2004), *Journal of Hydrometeorology*, **5**(4).

Dudhia, J., 1989: Numerical study of convection observed during the winter monsoon experiment using a mesoscale two-dimensional model. *J. Atmos. Sci.*, **46**, 3077-3107.

Dudhia, J., 1996: A multi-layer soil temperature model for MM5. In: Preprints, The sixth PSU/NCAR Mesoscale Model Users Workshop, 22-24 July 1996, Boulder, Colorado, pp. 49-50.

Dudhia, J., S.-Y. Hong, and K.-S. Lim, 2008: A new method for representing mixed-phase particle fall speeds in bulk microphysics parameterizations. *J. Met. Soc. Japan*, Vol. 86A, pp. 33-44.

EGCP, 2001: (<http://meted.ucar.edu/nwp/pcu2/etapcp1.htm>).

Eliasson, J., 1997: A Statistical Model for Extreme Precipitation. *Water Resources Research*, **33**(3), 449-455.

Federico, S., E. Avolio, C. Bellecci, M. Colacino, and R.L. Walko, 2006: Application of the LEPS technique for Quantitative Precipitation Forecasting (QPF) in Southern Italy: a preliminary study, *Nonlin. Processes Geophys.*, **13**, 53-66.

Frank, W.M. and C. Cohen, 1987: Simulation of tropical convective systems. Part I: A cumulus parameterization. *J. Atmos. Sci.*, **44**, 3787-3799.

Frank, W.M., and J. Molinari, 1993: Convective adjustment. The Representation of Cumulus Convection in Numerical Models, *Meteor. Monogr.*, **46**, Amer. Meteor. Soc., 101-106.

Fritsch, J.M., and C.F. Chappell, 1980: Numerical prediction of convectively driven mesoscale pressure systems. Part I: Convective parameterization. *J. Atmos. Sci.*, **37**, 1722-1733.

Fuller, W.E., 1914: Flood flows. *Trans. of the Amer. Soc. Of Civil Engineers*, **77**, 564-617.

Ghahraman, B., 2008: The Estimation of One Day Duration Probable Maximum Precipitation over Atrak Watershed In Iran, *Iranian Journal of Science And Technology Transaction B-Engineering*, **32**(B2), 175-179.

Grell, G.A., 1993: Prognostic Evaluation of assumptions used by cumulus parameterizations. *Mon. Wea. Rev.*, **121**, 764-787.

Grell, G.A., and D. Devenyi, 2002: A generalized approach to parameterizing convection combining ensemble and data assimilation techniques. *Geophys. Res. Lett.*, **29**(14), 1693, doi: 10.1029/2002GL015311.

Guttman, I., S.S. Wilks, and J.S. Hunter, 1982: Introductory Engineering Statistics, Third Edition, Wiley Series in Probability and Mathematical Statistics-Applied, John Wiley and Sons, 580 pp.

Hack, J.J., B.A. Boville, B.P. Briegleb, J.T. Kiehl, P.J. Rasch, and D.L. Williamson, 1993: Description of the NCAR Community Climate Model (CCM2). NCAR Tech. Note, NCAR/TN-382+STR, National Center for Atmospheric Research, Boulder, CO, 108 pp.

Haltiner, G.J., and R.T. Williams, 1980: Numerical prediction and dynamic meteorology. John Wiley & Sons, Inc., 477 pp.

Hansen, E.M., 1975: Probable Maximum Precipitation for Southwestern United-States, *Bulletin of the American Meteorological Society*, **56**(12), 1324-1324.

Hansen, E.M., 1987: Probable Maximum Precipitation for Design Floods In The United-States. *Journal of Hydrology*, **96**(1-4), 267-278.

Hansen, E.M., L.C., Schreiner, and J.F. Miller, 1982: Application of probable maximum precipitation estimates, United States east of the 105th meridian, Hydrometeorological Report No. 52, National Weather Service, US Dept. Commer., Silver Spring, Md., 169 pp.

Hansen, E.M., Schreiner, L.C., and Miller, J.F., 1994: Probable Maximum Precipitation - Pacific Northwest States. Columbia River (including portions of Canada), Snake River and Pacific Coastal Drainages, Hydrometeorological Report No. 57, National Weather Service, US Dept. Commer., Silver Spring, Md., 228 pp.

Hersfield, D.M., 1961: Estimating the probable maximum precipitation. *J. Hydraul. Div. Am. Soc. Civ. Eng.*, **87**, 99-106.

Hersfield, D.M., 1965: Method for estimating probable maximum precipitation. *J. Am. Waterworks Assoc.*, **57**, 965-972.

Higgins, R.W., and Mo, K.C., 1997: Persistent North Pacific circulation anomalies and the tropical intraseasonal oscillation. *J. Climate*, **10**, 223-244.

Higgins, R.W., J.K.E. Schemm, W. Shi, and A. Leetmaa, 2000: Extreme Precipitation Events in the Western United States Related to Tropical Forcing. *J. Climate*, **13**, 793-820.

Hong, S.-Y., J. Dudhia, and S.-H. Chen, 2004: A Revised Approach to Ice Microphysical Processes for the Bulk Parameterization of Clouds and Precipitation. *Mon. Wea. Rev.*, **132**, 103-120.

- Hong, S.-Y., and J.-O. J. Lim, 2006: The WRF Single-Moment 6-Class Microphysics Scheme (WSM6). *J. Korean Meteor. Soc.*, **42**, 129–151.
- Hong, S.-Y., Y. Noh, and J. Dudhia, 2006: A new vertical diffusion package with an explicit treatment of entrainment processes. *Mon. Wea. Rev.*, **134**, 2318–2341.
- Hong, S.-Y., and H.-L. Pan, 1996: Nonlocal boundary layer vertical diffusion in a medium-range forecast model, *Mon. Wea. Rev.*, **124**, 2322–2339.
- Hong, S.-Y., and Kim, S.-W., 2007: Stable Boundary Layer Mixing in a Vertical Diffusion Scheme, 18th Symposium on Boundary Layers and Turbulence (9–13 June 2008), Stockholm, Sweden.
- Hua, J., Y. Wu, and Y. Miao, 2006: One Calculating Method for Probable Maximum Precipitation of Short Duration, *Water Resources and Power*, **24**(6), 33–35.
- IPCC, 2009: http://www.ipcc-wg2.gov/AR5/extremes-sr/Index_extremes.html
- Janjic, Z.I., 1994: The step-mountain eta coordinate model: further developments of the convection, viscous sublayer and turbulence closure schemes. *Mon. Wea. Rev.*, **122**, 927–945.
- Janjic, Z.I., 2000: Comments on "Development and Evaluation of a Convection Scheme for Use in Climate Models". *J. Atmos. Sci.*, **57**, 3686.
- Janjic, Z.I., 2002: Nonsingular Implementation of the Mellor–Yamada Level 2.5 Scheme in the NCEP Meso model, *NCEP Office Note*, No. 437, 61 pp.
- Jeevarathnam, K., and M. Jayakumar, 1981: Estimation of Extreme Rainfall over Nilgiris South India, *Indian Forester*, **107**(10), 659–664.
- Joshi, P.C., and D.R. Sikka, 1986: A review of stochastic dynamic method of weather prediction. *Journal of Earth System Science*, **95**(3), 485–503.
- Jones, C., 2000: Occurrence of Extreme Precipitation Events in California and Relationships with the Madden–Julian Oscillation. *J. Climate*, **13**, 3576–3587.
- Kahya E., and J.A. Dracup, 1994: The influences of type 1 El Niño and La Niña events on streamflows in the Pacific Southwest of the United States. *J. Climate*, **7**, 965–976.
- Kain, J.S., 2004: The Kain-Fritsch convective parameterization: An update. *J. Appl. Meteor.*, **43**, 170–181.
- Kain, J.S., and J.M. Fritsch, 1990: A one-dimensional entraining/detraining plume model and its application in convective parameterization, *J. Atmos. Sci.*, **47**, 2784–2802.
- Kain, J.S., and J.M. Fritsch, 1993: Convective parameterization for mesoscale models: The Kain-Fritsch scheme, The representation of cumulus convection in numerical models, K. A. Emanuel and D.J. Raymond, Eds., Amer. Meteor. Soc., 246 pp.
- Kalnay, E., et al., 1996: The NCEP/NCAR 40-year reanalysis project. *Bulletin of the American Meteorological Society*, **77**(3), 437–471.

Kalnay E., 2003: Atmospheric modeling, data assimilation and predictability. Cambridge Univ. Press, 341 pp.

Kennedy, M.R., and T.L. Hart, 1984: The Estimation of Probable Maximum Precipitation in Australia, *Transactions of the Institution of Engineers, Australia, Civil Engineering* | *Transactions of The Institution of Engineers, Australia, Civil Engineering*, Ce26(1), 29-37.

Kessler, E., 1969: On the distribution and continuity of water substance in atmospheric circulation. *Meteor. Monogr.*, **32**, Amer. Meteor. Soc., 84 pp.

Koutsoyiannis, D., 1999: A Probabilistic View of Hershfield's Method for Estimating Probable Maximum Precipitation, *Water Resources Research*, **35**(4), 1313-1322.

Koutsoyiannis, D., 2004a: Statistics of Extremes and Estimation of Extreme Rainfall: I. Theoretical Investigation. *Hydrological Sciences Journal-Journal Des Sciences Hydrologiques*, **49**(4), 575-590.

Koutsoyiannis, D., 2004b: Statistics of Extremes and Estimation of Extreme Rainfall: II. Empirical Investigation of Long Rainfall Records, *Hydrological Sciences Journal-Journal Des Sciences Hydrologiques*, **49**(4), 591-610.

Koutsoyiannis, D., and G. Baloutsos, 2000: Analysis of a Long Record of Annual Maximum Rainfall in Athens, Greece, and Design Rainfall Inferences. *Natural Hazards*, **22**(1), 29-48.

Kulkarni, B. D., and S. Nandargi, 1996: Severe Rainstorms in the Vidarbha Subdivision of Maharashtra State, India. *Climate Research*, **6**(3), 275-281.

Laprise, R., 1992: The Euler equations of motion with hydrostatic pressure as an independent variable. *Mon. Wea. Rev.*, **120**, 197-207.

Levenson, V. H., 1986: Rainfall Characteristics of the Prescott, Arizona, Storm of 23-24 September 1983. *Monthly Weather Review*, **114**(12), 2344-2351.

Lin, Y.-L., R.D. Farley, and H.D. Orville, 1983: Bulk parameterization of the snow field in a cloud model. *J. Climate Appl. Meteor.*, **22**, 1065-1092.

Lynn, B., and A. Khain, 2007: Utilization of spectral bin microphysics and bulk parameterization schemes to simulate the cloud structure and precipitation in a mesoscale rain event. *J. Geophys. Res.*, **112**, D22205, doi:10.1029/2007JD008475.

Madden, R.A., and P.R. Julian, 1994: Observations of the 40-50-Day Tropical Oscillation—A Review. *Mon. Wea. Rev.*, **122**, 814-837.

Maxwell, R.M., F.K. Chow, and S.J. Kollet, 2007: The groundwater-land-surface-atmosphere connection: soil moisture effects on the atmospheric boundary layer in fully-coupled simulations, *Advances in Water Resources*, **30**(12), 2447-2466.

McCumber, M., W.-K. Tao, J. Simpson, R. Penc, and S.-T. Soong, 1991: Comparison of ice phase microphysical parameterization schemes using numerical simulations of tropical convection, *J. Appl. Meteor.*, **30**, 985-1004.

- Mellor, G.L., and T. Yamada, 1982: Development of a turbulence closure model for geophysical fluid problems. *Rev. Geophys. Space Phys.*, **20**, 851–875.
- Miami Conservancy District, State of Ohio, 1936: Storm rainfall of eastern United States (Revised). *Tech. Report*, Part V, Dayton, Ohio, 352 pp.
- Mlawer, E.J., S.J. Taubman, P.D. Brown, M.J. Iacono, and S.A. Clough, 1997: Radiative transfer for inhomogeneous atmosphere: RRTM, a validated correlated-k model for the longwave. *J. Geophys. Res.*, **102** (D14), 16663–16682.
- Mo K.C., and R. W. Higgins, 1998a: The Pacific South American modes and tropical convection during the Southern Hemisphere winter. *Mon. Wea. Rev.*, **126**, 1581–1598.
- Mo, K.C., and R.W. Higgins, 1998b: Tropical Influences on California Precipitation. *J. Climate*, **11**, 412–430.
- Mo, K.C., 1999: Alternating Wet and Dry Episodes over California and Intraseasonal Oscillations. *Mon. Wea. Rev.*, **127**, 2759–2776.
- Morgan, A.E., 1914: Discussion on flood flows. *Trans. of the Amer. Soc. of Civil Engineers*, **77**, 618–621.
- Morrison, H., J.A. Curry, and V.I. Khvorostyanov, 2005: A new double-moment microphysics parameterization for application in cloud and climate models, Part I: Description. *J. Atmos. Sci.*, **62**, 1665–1677.
- Morrison, H., and J.O. Pinto, 2006: Intercomparison of bulk microphysics schemes in mesoscale simulations of springtime Arctic mixed-phase stratiform clouds. *Mon. Wea. Rev.*, **134**, 1880–1900.
- Morrison, H., G. Thompson, and V. Tatarskii, 2009: Impact of Cloud Microphysics on the Development of Trailing Stratiform Precipitation in a Simulated Squall Line: Comparison of One- and Two-Moment Schemes. *Mon. Wea. Rev.*, **137**, 991–1007.
- Myers, V.A., 1967: Meteorological Estimation of Extreme Precipitation For Spillway Design Floods, in *Weather Bureau Technical Memorandum WBTM HYDRO-5*, edited, US Department of Commerce Environmental Science Services Administration Weather Bureau Office of Hydrology.
- National Research Council, 1983: Safety of Existing Dams Evaluation and Improvement, National Academy Press, 354 pp.
- National Research Council, C. o. M. A., Prediction, and Research, Board on Atmospheric Sciences and Climate, 1994: Estimating Bounds on Extreme Precipitation Events: A Brief Assessment, The National Academies Press, 29 pp.
- Nakazawa, T., 1986: Untraseasonal variations in OLR in the tropics during the FGG3 year. *J. Meteor. Soc. Japan*, **64**, 17–34.

NOAA, 1997: CNRFC Storm Summaries – December 26, 1996 – January 3, 1997., http://www.cnrfc.noaa.gov/storm_summaries/jan1997storms.php

Nobilis, F., T. Haiden, and M. Kerschbaum, 1991: Statistical Considerations Concerning Probable Maximum Precipitation (PMP) in the Alpine Country of Austria. *Theoretical And Applied Climatology*, **44**(2), 89-94.

Palmen, E., and E.O. Holopainen, 1962: Divergence, vertical velocity and conversion between potential and kinetic energy in an extratropical disturbance. *Geophysica*, **8**, 89-113.

Pielke, R.A, Sr., 2002: Mesoscale meteorological modeling. 2nd Edition, Academic Press, San Diego, CA.

Piper, B.S., J.V. Sutcliffe, and Y. P. Parks, 1994: The Victoria Project, Sri-Lanka Hydrological Analysis for Victoria Dam, *Proceedings of the Institution of Civil Engineers-Water Maritime and Energy*, **106**(1), 43-52.

Pleim, J.E., 2007: A combined local and non-local closure model for the atmospheric boundary layer. Part 1: Model description and testing. *J. Appl. Meteor. and Clim.*, **46**, 1383–1395.

Rafael, M., and G. Mills, 1996: The Role of Mid-Latitude Pacific Cyclones in the Winter Precipitation of California, *Professional Geographer*, **48**(3), 251-262.

Rakhecha, P.R., and M.R. Kennedy, 1985: A Generalized Technique for the Estimation of Probable Maximum Precipitation in India, *Journal of Hydrology*, **78**(3-4), 345-359.

Rakhecha, P.R., and B.D. Kulkarni, 1993: Probable Maximum Precipitation over Tamil Nadu-a Generalised Approach, *Mausam* | *Mausam*, **44**(3), 249-254.

Rakhecha, P.R., and M.K. Soman, 1994: Estimation of Probable Maximum Precipitation for a 2-Day Duration: Part 2-North Indian Region, *Theoretical and Applied Climatology*, **49**(2), 77-84.

Rakhecha, P. R., and C. Clark, 1999: Revised Estimates of One-Day Probable Maximum Precipitation (PMP) for India, *Meteorological Applications*, **6**(4), 343-350.

Rakhecha, P.R., and C. Clark, 2000: Point and Areal PMP Estimates for Durations of Two and Three Days in India, *Meteorological Applications*, **7**(1), 19-26.

Rakhecha, P.R., N.R. Deshpande, and M.K. Soman, 1992a: Probable Maximum Precipitation For a 2-Day Duration over The Indian Peninsula, *Theoretical and Applied Climatology*, **45**(4), 277-283.

Rakhecha, P.R., N.R. Deshpande, and M.K. Soman, 1992b: Estimation of Probable Maximum Precipitation and Maximum Rainfall for Different Recurrence Intervals for 2-Day Duration over Gujarat, *Indian Journal of Power and River Valley Development* | *Indian Journal of Power and River Valley Development*, **42**(7), 231-235.

- Rakhecha, P.R., B.N. Mandal, A.K. Kulkarni, and N.R. Deshpande, 1995a: Estimation of Probable Maximum Precipitation for Catchments in Eastern India by a Generalized-Method. *Theoretical And Applied Climatology*, **51**(1-2), 67-74.
- Rakhecha, P.R., N.R. Deshpande, A.K. Kulkarni, B.N. Mandal, and R.B. Sangam, 1995b: Design Storm Studies for the Upper Krishna River Catchment Upstream of the Almatti Dam Site. *Theoretical And Applied Climatology*, **52**(3-4), 219-229.
- Rasmussen, C. 1999. Weather research and forecasting model. UCAR Quarterly 24, 10-11.
- Reisner, J.R., R.M. Rasmussen, and R.T. Bruintjes, 1998: Explicit forecasting of supercooled liquid water in winter storms using the MM5 mesoscale model. *Quart. J. Roy. Meteor. Soc.*, **124**, 1071–1107.
- Rezacova, D., P. Pesice, and Z. Sokol, 2005: An Estimation of the Probable Maximum Precipitation for River Basins in the Czech Republic. *Atmospheric Research*, **77**(1-4), 407-421.
- Ropelewski C.F., and M.S. Halpert, 1986: North American precipitation and temperature patterns associated with the El Niño/Southern Oscillation (ENSO). *Mon. Wea. Rev.*, **114**, 2352–2362.
- Rutledge, S.A. and P.V. Hobbs, 1983: The mesoscale and microscale structure and organization of clouds and precipitation in midlatitude cyclones, VIII: A model for the "seeder-feeder" process in warm-frontal rainbands. *J. Atmos. Sci.*, **40**, 1185-1206.
- Rutledge, S.A., and P.V. Hobbs, 1984: The mesoscale and microscale structure and organization of clouds and precipitation in midlatitude cyclones. XII: A diagnostic modeling study of precipitation development in narrow cloud-frontal rainbands. *J. Atmos. Sci.*, **20**, 2949–2972.
- Ryan, B.F, 1996: On the global variation of precipitating layer clouds. *Bull. Amer. Meteor. Soc.*, **77**, 53-70.
- Schreiner, L.C., 1978: Evaluation of Probable Maximum Precipitation for United-States East of 105th-Meridian, *Transactions-American Geophysical Union*, **59**(12), 1062.
- Sharma, S.C., K. Mukherjee, and B.C. Jain, 1988: Estimation of Probable Maximum Precipitation for Bargi Catchment up to Jamtara Dam Site in Madhya Pradesh, *Mausam* | *Mausam*, **39**(2), 187-192.
- Shepherd, D.J., and J.R. Colquhoun, 1985: Meteorological Aspects of an Extraordinary Flash Flood Event Near Dapto, New South Wales. *Australian Meteorological Magazine* | *Australian Meteorological Magazine*, **33**(2), 87-102.
- Schonher T., and S.E. Nicholson, 1989: The relationship between California rainfall and ENSO events. *J. Climate*, **2**, 1258–1269.
- Showalter, A. K. and S.B. Solot 1942: Computation of maximum possible precipitation, *Trans. Am. Geophys. Union*, **2**, 258–274.

Singh, R.S., Y.S. Ramakrishna, K.D. Sharma, R.S. Purohit, and D.N. Bohra, 1992: Some Hydrometeorological Aspects of an Unprecedented Rainstorm in the Indian Desert, *Annals of Arid Zone*, **31**(3), 205-210.

Skamarock, W.C., J. B. Klemp, J. Dudhia, D.O. Gill, D.M. Barker, M.G. Duda, X. Huang, W. Wang, and J.G. Powers, 2008: A description of the Advanced Research WRF Version 3. NCAR Tech. Note, NCAR/TN-475+STR, 125 pp.

Stull, R.B., 1988. An Introduction to Boundary Layer Meteorology. Kluwer Academic Publishers, Dordrecht, 666 pp.

Svensson, C., and P.R. Rakhecha, 1998: Estimation of Probable Maximum Precipitation for Dams in the Hongru River Catchment, China, *Theoretical and Applied Climatology*, **59**(1-2), 79-91.

Tao, W.-K., and J. Simpson, 1993: The Goddard cumulus ensemble model. Part I: Model description. *Terr. Atmos. Oceanic Sci.*, **4**, 35–72.

Tao, W.-K., J. Simpson, and M. McCumber, 1989: An ice-water saturation adjustment, *Mon. Wea. Rev.*, **117**, 231–235.

Tao, W.-K., J. Simpson, D. Baker, S. Braun, M.-D. Chou, B. Ferrier, D. Johnson, A. Khain, S. Lang, B. Lynn, C.-L. Shie, D. Starr, C.-H. Sui, Y. Wang, and P. Wetzel, 2003: Microphysics, radiation and surface processes in the Goddard Cumulus Ensemble (GCE) model. *Meteor. and Atmos. Phys.*, **82**, 97–137.

The ARW-Version3 (see Skamarock et al., 2008)

Thompson, G., R.M. Rasmussen, and K. Manning, 2004: Explicit Forecasts of Winter Precipitation Using an Improved Bulk Microphysics Scheme. Part I: Description and Sensitivity Analysis. *Mon. Wea. Rev.*, **132**, 519–542.

Thompson, G., P.R. Field, R.M. Rasmussen, and W.D. Hall, 2008: Explicit Forecasts of Winter Precipitation Using an Improved Bulk Microphysics Scheme. Part II: Implementation of a New Snow Parameterization. *Mon. Wea. Rev.*, **136**, 5095–5115.

Thompson, S.M., 2003: Duration of Probable Maximum Precipitation on Lake Catchments: Alternative Analysis, *Journal of Hydrologic Engineering*, **8**(4), 190-196.

Trenberth, K.E. and J.W. Hurrell, 1994: Decadal atmosphere-ocean variations in the Pacific, *Climate Dynamics*, **9**, 303-319.

Troen, I.B., and L. Mahrt, 1986: A Simple Model of the Atmospheric Boundary Layer; Sensitivity to surface Evaporation, *Boundary Layer Meteorology*, **37**, 129-148.

USACE 2005: Stochastic modeling of extreme floods on the American River at Folsom Dam, Appendix C- 72-hour precipitation-frequency relationship and uncertainty analysis for the 1860-mi² American River Watershed, RD-48C, US Army Corps of Engineers, Hydrologic Engineering Center, 27 pp.

U.S. Weather Bureau, 1961: Interim Report Probable Maximum Precipitation in California. Hydrometeorological Report No. 36. Hydrometeorological Section, Washington, D.C., 202 pp.

U.S. Weather Bureau, 1969: Interim Report Probable Maximum Precipitation in California-Revised. Hydrometeorological Report No. 36, U.S. Department of Commerce, Washington, D.C., 207 pp.

Wallace, J.M., and D.S., Gutzler, 1981: Teleconnections in the Geopotential Height Field during the Northern Hemisphere Winter, *Monthly Weather Review*, **109**, 784-812.

Wallace, J.M. and P.V. Hobbs, 1977: Atmospheric Science an Introductory Survey, Academic Press, 467 pp.

Wallace, J.M. and P.V. Hobbs, 2006: Atmospheric Science an Introductory Survey, 2nd Edition, Academic Press, 467 pp.

Wang, B.H., 1984: Estimation of Probable Maximum Precipitation - Case Studies, *Journal of Hydraulic Engineering-Asce*, **110**(10), 1457-1472.

Wang P.K., and W. Ji, 2000: Collision efficiencies of ice crystals at low-intermediate Reynolds numbers colliding with supercooled cloud droplets: A numerical study. *J. Atmos. Sci.*, **57**, 1001–1009.

Weickmann, K.M., G.R. Lussky, and J.E. Kutzbach, 1985: Intraseasonal (30-60 day) fluctuations of outgoing longwave radiation and 250 mb stream function during northern winter. *Mon. Wea. Rev.* **113**(6), 941-961.

Wicker, L.J., and W.C. Skamarock, 2002: Time-Splitting Methods for Elastic Models Using Forward Time Schemes. *Mon. Wea. Rev.*, **130**, 208–209.

Wicker, L.J., and R.B. Wilhelmson, 1995: Simulation and analysis of tornado development and decay within a three-dimensional supercell thunderstorm. *J. Atmos. Sci.*, **52**, 2675–2703.

Wiesner, C.J., 1970: Estimation of Probable Maximum Precipitation, *Proceedings of The Institution of Civil Engineers*, **47**, 297-&.

World Meteorological Organization, 1986: Manual for estimation of probable maximum precipitation. Operational Hydrology Report No.1, Second Edition, Geneva, 269 pp.

Zhan, D., and J. Zou, 1986: The Progress of Probable Maximum Precipitation (PMP) and Probable Maximum Floods (PMF) Estimation Stutier in China, *Acta Meteorologica Sinica* | *Acta Meteorologica Sinica*, **44**(4), 473-481.

Zhan, D.J., and J.S. Zhou, 1984: Recent Developments on the Probable Maximum Precipitation (PMP) Estimation in China, *Journal of Hydrology*, **68**(1-4), 285-293.

Zhao, W.J., J.A. Smith, and A.A. Bradley, 1997: Numerical Simulation of a Heavy Rainfall Event During the Pre-Storm Experiment, *Water Resources Research*, **33**(4), 783-799.