

Global Guide to Tropical Cyclone Forecasting

Introduction

This electronic publication of the World Meteorological Organization (WMO) is aimed to serve as a platform for the information sources for tropical cyclone forecasters to obtain data and tools which are useful for monitoring and forecasting of tropical cyclones. Forecasters may access the various sources providing conventional and specialized data/products including those from numerical predictions and remote sensing observations as well as forecasting tools concerning tropical cyclone development, motion, intensification and wind distribution. It will continue to develop along with the availability of new data and products and will also contain techniques and best practices from tropical cyclone forecast centers that could be adapted by other forecast centers. This Training manual has been developed using contributions from various authors around the world. It will be updated from time to time as the science and practice of Tropical Cyclone monitoring and forecasting evolves. The multi-author nature of this document means that both British and American spellings will appear across various parts of the document. Figure 1 is a taste of the imagery types included in the Guide.

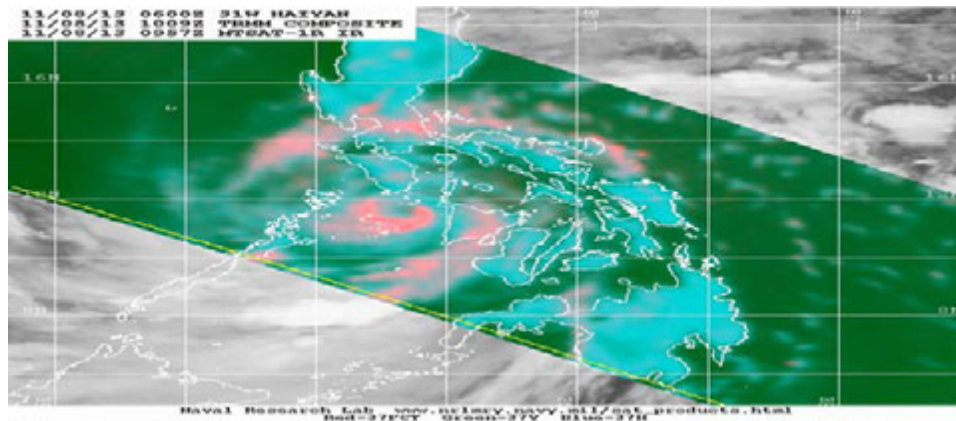


Figure 1 shows an example of a 37-GHz polarized corrected temperature (PCT) image of Super Typhoon Haiyan on 8 November 2013, where blue-green streamers indicate low cloud bands and reds and pinks indicate well-developed convective clouds. Dark green patches, represent areas that are the same temperature as the ocean surface. The green spot inside the pink ring indicates the partially cloud-free eye. Analysis of multiple images (preferably within six hours of the analysis time) can increase the chances of correctly identifying the TC center. Sequential multiple images can be animated to improve center location of poorly organized systems (Edson, personal communication). (Image courtesy of the US Naval Research Laboratory).

Table of Contents

| | |
|--|-----------|
| Global Guide to Tropical Cyclone Forecasting | 0 |
| Chapter One | 9 |
| <i>1. Global Guide to Tropical Cyclone Forecasting Overview.....</i> | <i>9</i> |
| 1.1 Introduction and purpose | 9 |
| 1.1.2 Tropical Cyclone Climatology (Neumann) | 10 |
| 1.1.3 Tropical Cyclone Motion (Kimberlain and Brennen) | 10 |
| 1.1.4 Tropical Cyclone Structure (Evans)..... | 11 |
| 1.1.5 Storm Surge and Open Ocean Waves (Lyons) | 11 |
| 1.1.6 Tropical Cyclone Hydrology (Lai et al.) | 12 |
| 1.1.7 Seasonal Forecasting (Klotzbach et al.) | 12 |
| 1.1.8 Forecasting Strategy (Burton et al.)..... | 12 |
| 1.1.9 Warning Strategy (Guard)..... | 13 |
| 1.1.10 Training materials (Guard)..... | 13 |
| 1.1.11 Ready Reckoner | 13 |
| 1.2 The global tropical cyclone forecasting network | 13 |
| 1.2.1 Tropical cyclone warnings | 16 |
| 1.2.2 Naming of tropical cyclones | 22 |
| 1.2.3 Terminology..... | 23 |
| 1.3 References | 25 |
| Chapter Two | 26 |
| <i>2. A Global Tropical Cyclone Climatology.....</i> | <i>26</i> |
| 2.1 Introduction and purpose | 26 |
| 2.1.1 About historical TC data | 28 |
| 2.1.2 On the quality of TC data..... | 29 |
| 2.1.3 Basin boundaries | 30 |
| 2.1.4 Wind averaging times..... | 31 |
| 2.2. Chart preparation | 32 |
| 2.2.1 Tropical cyclone tracks | 33 |
| 2.2.3 Tropical cyclone track density | 35 |
| 2.2.4 Motion parameters | 36 |
| 2.2.5 TC vector direction | 38 |
| 2.2.6 Vector and scalar speeds..... | 39 |
| 2.2.7 Global values of the steadiness index | 40 |
| 2.3 Tabular data | 41 |

| | |
|---|------------|
| 2.3.1 Seasonal summaries | 41 |
| 2.3.2 Other comments on seasonal summaries | 45 |
| 2.4 Meridional profiles..... | 45 |
| 2.4.1 Translational motion | 46 |
| 2.4.2 Meridional values of steadiness index | 46 |
| 2.5 Intra-seasonal TC occurrence..... | 49 |
| 2.6 Some statistical considerations..... | 52 |
| 2.6.1 Binomial and Poisson distributions | 52 |
| 2.6.2 Mixed distributions..... | 53 |
| 2.6.2.1 TC motion (bivariate normal distribution) | 53 |
| 2.6.2.2 TC wind (Weibull distribution) | 53 |
| 2.6.3 Other TC related distributions..... | 55 |
| 2.6.4 Additional remarks | 56 |
| 2.7 References | 56 |
| Chapter Three..... | 61 |
| 3. <i>Tropical Cyclone Motion</i> | 61 |
| 3.1 Introduction | 61 |
| 3.2 Position analysis | 61 |
| 3.3 TC track forecasting | 88 |
| 3.4 Summary and conclusions | 117 |
| 3.5 Acknowledgements..... | 118 |
| 3.6 References | 118 |
| Chapter Four..... | 124 |
| 4. <i>Tropical Cyclone Intensity, Structure, and Structure Change</i> | 124 |
| 4.1 Introduction ¹ | 124 |
| 4.2 Necessary ingredients for tropical cyclogenesis | 125 |
| 4.3 Tropical cyclone structure needed for genesis and intensification to continue..... | 126 |
| 4.4 Regional sources of disturbances that can develop into tropical cyclones | 129 |
| 4.5 Mechanisms for generation of tropical disturbances | 131 |
| 4.6 Favorable conditions for the evolution of a tropical disturbance into a tropical storm..... | 135 |
| 4.7 Tropical cyclone intensity and mechanisms of intensity change..... | 136 |
| 4.8 References | 150 |
| Chapter Five..... | 155 |
| 5. <i>Tropical Cyclone Storm Surge and Open Ocean Waves</i> | 155 |

| | |
|---|------------|
| 5.1 Introduction | 155 |
| 5.2 Wave growth..... | 155 |
| 5.3 Wave spectrum | 156 |
| 5.4 Wind fetch length | 158 |
| 5.5 Wind duration | 160 |
| 5.6 Tropical cyclone swells..... | 164 |
| 5.7 Radius of 12 foot seas vs coastal wave heights | 167 |
| 5.8 Coastal surf | 167 |
| 5.9 Tropical cyclone wave/swell setup & run-up..... | 168 |
| 5.10 Some specific forecast problems | 171 |
| 5.10.1. Trapped fetch (contributed by Mr. Jeff Callaghan) | 171 |
| 5.10.2 Storm surge probabilities | 177 |
| 5.10.3 Summary..... | 177 |
| Chapter Six | 179 |
| <i>6. Tropical Cyclone Rainfall and Flood Forecasting.....</i> | <i>179</i> |
| 6.1 Introduction and basic hydrology | 179 |
| 6.1.1 Surface runoff..... | 179 |
| 6.1.2 Interflow | 180 |
| 6.1.3 Basin properties..... | 180 |
| 6.1.4 Pre-event water | 181 |
| 6.2 Types of flooding..... | 181 |
| 6.2.1 Flash flooding | 181 |
| 6.2.2 Area and inland flooding | 182 |
| 6.2.3 River flooding..... | 182 |
| 6.2.4 Mudslides and debris flows | 183 |
| 6.3 Satellite techniques..... | 185 |
| 6.3.1 Technological advances | 185 |
| 6.3.2 Quantitative precipitation estimation (QPE) | 187 |
| 6.3.3 Flood monitoring | 190 |
| 6.4 Radar techniques | 191 |
| 6.4.1 Overview..... | 191 |
| 6.4.2 Radar quantitative precipitation estimates (QPE)..... | 192 |
| 6.4.3 Rain characteristics..... | 194 |
| 6.4.4 Future development | 194 |
| 6.5 Raingauge networks and techniques | 194 |
| 6.5.1 Gauge-based statistical models | 194 |
| 6.5.2 Asymmetry and topographic effects | 196 |

| | |
|---|------------|
| 6.6 Synoptic and climatological techniques..... | 199 |
| 6.6.1 Climatological patterns..... | 199 |
| 6.6.2 Rainfall patterns in and around the cyclone..... | 200 |
| 6.6.3 Orographic effect and landfall..... | 201 |
| 6.7 QPF products..... | 202 |
| 6.7.1 Numerical and satellite-based products..... | 202 |
| 6.7.2 Multi-model ensemble | 205 |
| 6.7.3 Radar-based now casting application..... | 207 |
| 6.7.4 Verification | 207 |
| 6.8 Flood forecasting | 208 |
| 6.8.1 Hydrological tools and models | 208 |
| 6.8.2 Operational products..... | 209 |
| 6.8.3 A forecast technique for diagnosing areas of extreme rainfall | 210 |
| 6.8.3.1 Typhoon Bilis | 210 |
| 6.8.3.2 Hurricane Mitch | 213 |
| 6.8.3.3 Vietnam floods of November 1999 | 214 |
| 6.8.3.4 Mumbai Floods..... | 215 |
| 6.8.3.5 Typhoon Chata'an disaster in the Chuuk Lagoon Islands, FSM..... | 216 |
| 6.8.3.6 World record rainfall La Reunion | 218 |
| 6.8.4 Some still pertinent forecast hints from the previous Global Guide..... | 218 |
| 6.8.4.1. Quantitative prediction of tropical cyclone rainfall difficult for four reasons: | 218 |
| 6.8.4.2. Rainfall analysis and forecasting | 219 |
| 6.8.4.3. Determining threat areas..... | 219 |
| 6.8.4.4. Monitoring the event | 220 |
| 6.9. References | 220 |
| Chapter Seven | 228 |
| 7. <i>Seasonal Forecasting of Tropical Cyclones</i> | 228 |
| 7.1 Introduction | 228 |
| 7.2 Colorado State University seasonal hurricane outlooks | 232 |
| 7.3 NOAA seasonal hurricane outlooks | 235 |
| 7.4 City University of Hong Kong seasonal hurricane outlooks | 238 |
| 7.5 Tropical Storm Risk seasonal hurricane outlooks | 240 |
| 7.6 ECMWF seasonal hurricane outlooks | 245 |
| 7.7 IRI seasonal hurricane outlooks | 248 |
| 7.8 Summary | 255 |
| 7.9 Reference | 255 |
| Chapter Eight..... | 260 |

| | |
|---|-----|
| 8. Operational Strategy..... | 260 |
| 8.1 Introduction | 260 |
| 8.2 Infrastructure and systems | 261 |
| 8.2.1 Physical design of the forecast/warning office..... | 261 |
| 8.2.2 Technology and data access | 263 |
| 8.3 People | 266 |
| 8.3.1 Staffing..... | 266 |
| 8.3.2 Training | 267 |
| 8.3.3 Roles | 268 |
| 8.4 TCWC process and procedures | 269 |
| 8.4.1 A cyclical view of TCWC process..... | 270 |
| 8.4.2 Documenting procedures | 270 |
| 8.4.3 The critical time window | 270 |
| 8.4.4 Coping with the extraordinary..... | 272 |
| 8.5 Delivering the message | 273 |
| 8.5.1 Forecast dissemination..... | 273 |
| 8.5.2 Interaction with the media | 274 |
| 8.5.3 Social media..... | 275 |
| 8.5.4 Interaction with Emergency Management agencies | 276 |
| 8.6 Outreach and public education..... | 276 |
| 8.7 Continuous improvement | 277 |
| 8.7.1 Immediate post impact assessment | 277 |
| 8.7.2 Formal review/verification | 278 |
| 8.7.3 Preseason readiness | 279 |
| 8.8 A forecaster's operational strategy..... | 280 |
| 8.8.1 Know your operational plan | 280 |
| 8.8.2 Know your duties..... | 281 |
| 8.8.3 Know your equipment | 281 |
| 8.8.4 Try to anticipate cyclogenesis | 281 |
| 8.8.5 Locate the system centre as effectively as possible | 281 |
| 8.8.6 Use all available prediction techniques | 281 |
| 8.8.7 Keep a log | 282 |
| 8.8.8 Issue "now-time" warnings..... | 282 |
| 8.8.9 Know the danger zones for possible cyclone impact | 282 |
| 8.8.10 Keep your message clear | 282 |
| 8.8.11 "Double check" warning information | 283 |
| 8.8.12 Be responsive | 283 |
| 8.9 Summary | 283 |

| | |
|---|------------|
| 8.10 References | 285 |
| Appendix | 286 |
| Appendix 8.1 TCWC forecast process time line | 286 |
| Appendix 8.2 Tropical Cyclone Information Processing System (TIPS) at the Hong Kong Observatory | 287 |
| Appendix 8.3 Some capabilities at the RSMC - Tropical Cyclone Centre New Delhi | 287 |
| References | 292 |
| Chapter Nine..... | 293 |
| 9. <i>Warning Strategies</i> | 293 |
| 9.1 Introduction | 293 |
| 9.1.1 Purpose of strategies | 293 |
| 9.1.2 Objective of an integrated national warning service..... | 294 |
| 9.1.3 Forecast strategy | 294 |
| 9.1.4 Warning strategy | 295 |
| 9.1.5 Response strategy | 295 |
| 9.1.6 Help make critical decisions more effective | 295 |
| 9.2 The nature of warning and response | 296 |
| 9.2.1 Principles for good major hazard warnings | 296 |
| 9.2.2 Response to warnings: behavioral factors..... | 297 |
| 9.2.3 Warning strategies in an interdisciplinary perspective | 298 |
| 9.3 Operational strategies for tropical cyclone (TC) warning and response systems | 299 |
| 9.3.1 Warning and response system | 300 |
| 9.3.2 Warning and response phases..... | 302 |
| 9.4 Constraints that challenge warning strategies..... | 305 |
| 9.4.1 Forecast uncertainty..... | 306 |
| 9.4.2 Strike probability forecasts..... | 308 |
| 9.4.3 Expect the unusual, it is normal | 309 |
| 9.4.4 Warning content and terminology | 311 |
| 9.4.4.1 Forms of presentation..... | 312 |
| 9.4.4.2 Communicating forecast uncertainties | 314 |
| 9.4.4.3 From weather prediction to weather impacts prediction (National Research Council, 2010) | 317 |
| 9.4.5 Warning dissemination..... | 318 |
| 9.4.5.1 Various modes of warning dissemination..... | 318 |
| 9.4.5.2 Warnings to the last mile | 321 |
| 9.5 Hazard, vulnerability and risk assessment | 323 |

| | |
|--|------------|
| 9.5.1 Quantification of risk | 324 |
| 9.5.2 Hazard or threat assessment..... | 324 |
| 9.5.3 Vulnerability assessment..... | 326 |
| 9.5.4 Potential disaster risk scales..... | 328 |
| 9.5.5 Conveying forecast uncertainty..... | 328 |
| 9.6 Societal impacts of tropical cyclones | 329 |
| 9.6.1 Introduction..... | 329 |
| 9.6.2 Physical impacts of tropical cyclones on people and communities..... | 330 |
| 9.6.3 Physical impacts upon households and communities..... | 332 |
| 9.6.4 Psychological impacts upon households and communities | 332 |
| 9.6.5 Environmental damage | 333 |
| 9.7 Vulnerability and resilience..... | 333 |
| 9.8 Tropical cyclone hazard mitigation | 335 |
| 9.9 Economic impacts of tropical cyclones | 336 |
| 9.9.1 Loss normalization..... | 337 |
| 9.10 Future and current loss sensitivity..... | 342 |
| 9.11 Financial management of extreme events | 345 |
| 9.11.1 Catastrophe insurance: how it is changing in the US | 345 |
| 9.11.2 The disaster mitigation challenge..... | 346 |
| 9.11.3 Global risk financing in coming decades..... | 347 |
| 9.11.4 Integrating the financial management of disasters as part of a national strategy..... | 348 |
| 9.12 Acknowledgements..... | 348 |
| 9.13 References | 349 |
| 9.13.1 References | 349 |
| 9.13.2 References | 351 |
| Chapter Ten | 355 |
| <i>10 Tropical Cyclone Training</i> | <i>355</i> |
| 10.1 UCAR, COMET®, MetEd..... | 355 |
| 10.1.1 COMET/MetEd: Tropical/Hurricanes..... | 356 |
| 10.1.2 COMET/MetEd: Satellite Meteorology..... | 357 |
| 10.1.3 COMET/MetEd: Radar Meteorology | 357 |
| 10.1.4 COMET/MetEd: Oceanography/Marine Meteorology | 357 |
| 10.1.5 COMET/MetEd: Hydrology/Flooding..... | 358 |
| 10.1.6 COMET/MetEd: Emergency Management | 359 |
| 10.1.7 COMET/MetEd: Numerical Modeling..... | 359 |
| 10.2 WMO-sponsored training | 360 |
| 10.3 Regional training..... | 360 |

| | |
|--|------------|
| 10.3.1 National meteorological center-sponsored, RSMC-sponsored, and TCWC-sponsored training | 360 |
| 10.3.2 National and regional disaster risk reduction..... | 360 |
| 10.4 Internal training programs and certifications | 360 |
| 10.4.1 NOAA | 361 |
| 10.5 The function of training programs in tropical cyclone centers | 361 |
| 10.5.1 Certification training..... | 361 |
| 10.5.2 Recurrent training | 361 |
| 10.5.3. Advanced or specialized training..... | 362 |
| 10.6 WMO Tropical Cyclone Forecaster's Website..... | 362 |
| Chapter Eleven | 363 |
| <i>11. Ready Reckoner.....</i> | <i>363</i> |
| 11.1 Introduction | 363 |
| 11.2 Unit conversion | 363 |
| 11.3 Beaufort scale | 364 |
| 11.4 Useful tropical cyclone parameters | 367 |
| 11.4.1 Tropical cyclone severity scales | 367 |
| 11.4.2 Gust factors | 367 |
| 11.4.3 Dvorak intensity relationship..... | 368 |
| 11.5 Useful constants..... | 369 |
| 11.6 Derived parameters | 371 |
| 11.6.1 Definition of terms | 371 |
| 11.6.2 Derived parameters..... | 372 |
| 11.7 Tropical cyclone records | 377 |
| 11.7.1 Global records | 377 |
| 11.7.2 Regional Records | 379 |
| 11.8 Trivia corner | 379 |
| 11.9 References | 381 |
| Glossary..... | 383 |
| Acknowledgements | 396 |