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Handbook of Automated Data Quality Control Checks and Procedures

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GLOSSARY OF ACRONYMS AND ABBREVIATIONS

ADCP	Acoustic Doppler Current Profiler
ARES	Acquisition and Reporting Environmental System
C-MAN	Coastal-Marine Automated Network
CSOR	Critical System of Record
DART	Deep-ocean Reporting and Assessment of Tsunamis
DAS	Data Acquisition System
FFT	Fast Fourier transform
GOES	Geostationary Operational Environmental Satellite
GFS	Global Forecast System
GTS	Global Telecommunication System
MARS	Multifunction Acquisition and Reporting System
NCEI	National Centers for Environmental Information
NCEP	National Centers for Environmental Prediction
NDBC	National Data Buoy Center
NIST	National Institute of Standards and Technology
NMCA	Navy Marine Climatic Atlas
NOAA	National Oceanic and Atmospheric Administration
NTSC	NDBC Technical Services Contractor
NWS	National Weather Service
QARTOD	Quality Assurance/Quality Control of Real Time Oceanographic Data
QC	Quality Control
SCOOP	Self-Contained Ocean Observing Payload
SST	Sea Surface Temperature
TAO	Tropical Atmosphere Ocean
VOS	Voluntary Observing Ship

1. INTRODUCTION

The National Data Buoy Center (NDBC), a part of the National Oceanic and Atmospheric Administration's (NOAA) National Weather Service (NWS), operates and quality controls data from more than 100 moored Coastal Weather Buoys, 40 Coastal-Marine Automated Network (C-MAN) stations, 48 Tropical Atmosphere Ocean (TAO) array, and 39 Deep-Ocean Reporting and Assessment of Tsunamis (DART) tsunameter stations. In addition, NDBC quality controls and distributes environmental data from partner stations using our existing automated processes. NDBC also administers the Voluntary Observing Ship (VOS) program; however the VOS data are processed and quality controlled separately from the rest of NDBC's systems of record, and are outside the scope of this document. All NDBC and partner stations acquire environmental data primarily for weather warnings, analyses, and forecasts. Buoy data are also used to provide ground-truth measurements for space-based observation platforms and to establish long-term environmental records for engineering applications, climate research, and air-sea interaction studies. NDBC has developed the capability to make a variety of measurements, including:

- Atmospheric pressure
- Wind direction, speed, and gust
- Air temperature
- Sea surface water temperature
- Sub-surface water temperature
- Wave energy spectra (non-directional and directional)
- Water-column height (tsunami detection)
- Relative humidity and dew point
- Ocean current velocity and direction
- Precipitation
- Salinity
- Longwave solar radiation
- Shortwave solar radiation
- Hydrostatic water pressure (tsunami detection)

The NDBC and partner station networks consist of sites offshore and along most of the U.S. coastline, including Alaska, Hawaii, the Great Lakes, and U.S. territories. The maritime community has come to rely on the data for the safe conduct of maritime operations, and the networks often provide the only real-time measurements available from remote, data sparse areas.

1.1. PURPOSE

This handbook describes the automated quality control (QC) procedures used to ensure the accuracy of NDBC measurements. It may be used as a tutorial for newcomers to NDBC or as a reference for users of NDBC data. This handbook supersedes the August 2009 version of the handbook.

1.2. DATA USES

A key user of NDBC weather buoy observations is the NWS, which uses the data for the issuance of warnings, analyses, forecasts and for initializing numerical models. The general public has access to the data on the NDBC web site. All data collected on NDBC operated moored buoys and C-MAN stations are processed and archived at the National Centers for Environmental Information (NCEI). All archived data have been processed through automated QC checks and manual review, and have met NDBC standards for accuracy.

Recent data collected from NDBC's partner platforms are available on NDBC's website; however NDBC does not archive partner data at NCEI.

1.3. THE NDBC QC PROGRAM

The primary objective of the NDBC quality control and quality assurance process is to verify that NDBC observations are accurate and reliable while ensuring usability and confidence in the observations. NDBC sensor accuracy is determined in reference to a known National Institute of Standards and Technology (NIST) traceable standard. Where possible, NDBC also identifies errors or anomalies induced by the buoy or platform, and to some extent, the accuracy to which we can monitor the measurement in its remote environment. The accuracy of NDBC observations has improved through the years and is related to the technology used to collect and process the measurements. The accuracy of the current observations are given below in Table 1. The accuracy of historical observations can be found on the NDBC website at the following link: https://www.ndbc.noaa.gov/faq/rsa.shtml.

NDBC field comparisons show that observation accuracies (the accuracy of the observation collected during deployment) are often different from sensor accuracies stated on the instrument specifications collected in the lab or during controlled conditions. The environmental conditions will cause an additional induced error known as the observation uncertainty. For example, the total sensor accuracy for wind speed is plus or minus 1 m/s, yet there are some environmental conditions, such as high waves, which may temporarily degrade us from achieving the desired accuracies. Another example of uncertainty is related to sensor bio-fouling. Salinity sensors are very susceptible to this natural occurrence and, as a result, their accuracies are often degraded by an unknown value.

The NDBC QC processes may be viewed in two parts. First, there are real-time automated QC checks done exclusively by computer programs. These include gross error checks that detect communication transmission errors, missing data, and total sensor failure. Data flagged by these checks are likely to be erroneous. These checks, however, can be manually overridden when storms or other unusual environmental phenomena are anticipated to generate out of the ordinary, but valid measurements. Another category of automated checks identifies data that may not be grossly in error but are questionable, for example data outside of climatological limits. Data so identified will be released, but will undergo additional scrutiny within 24 hours by a data quality analyst.

The second part of the NDBC QC process entails manual checks by a data analyst. They perform manual inspection using computer-generated analytical aids, graphical displays, and the results of any automated QC checks to identify the often subtle degradation of systems and sensors. Analysts integrate and compare NDBC data with relevant products, such as weather observations, numerical weather analyses and forecasts, weather radar, and satellite images. Ultimately, all NDBC data are sent to the NOAA archive and will include their data quality flags, whereas only -valid data are released publicly on the NDBC website.

Table 1. Measurement accuracies of current observations by program

Observation	**Observing System of Record**		
	TAO	Coastal Weather Buoy/C-MAN	DART
Atmospheric Pressure	0.1 hPa or 0.01%	1.0 hPa	N/A
Wind Direction	5°	10°	N/A
Wind Speed	0.3 m/s or 3%	1.0 m/s or 10%	N/A
Air Temperature	0.2°C	1.0°C	N/A
Relative Humidity	2%	3%	N/A
Dew Point	N/A	1.0°C	N/A
Rain	1 mm	N/A	N/A
Shortwave Radiation	1%	N/A	N/A
Longwave Radiation	1%	N/A	N/A
Wave Height	N/A	0.2 m	N/A
Wave Period	N/A	1 s	N/A
Wave Direction	N/A	10°	N/A
Sea Surface Water Temperature	0.01°C	1.0°C	N/A
Subsurface Water Temperature	0.01°C	N/A	N/A
Salinity	0.02 psu	N/A	N/A
Water Pressure (mooring line)	0.1%	N/A	N/A
Water Pressure (seafloor)	N/A	N/A	0.1 psi
Ocean Currents (Point)	5 cm/s (speed) 5° (direction)	2 cm/s	N/A
Ocean Currents (Profile)	5 cm/s (speed) 5° (direction)	N/A	N/A

2. DATA FLOW AND PROCESSING

This section describes the most important data paths that are used by NDBC and its users to acquire NDBC data. The major steps involved in applying automated QC during the data production process are also briefly described.

2.1. DATA PATHS

The data paths for real-time and delayed mode (post-deployment) data from NDBC-operated platforms are shown in Figures 1 through 3.

For NDBC operated stations, the acquisition and telemetry of sensor data on each station are controlled by an onboard microprocessor(s) referred to as the Data Acquisition System (DAS) which transmits data via a communication satellite.

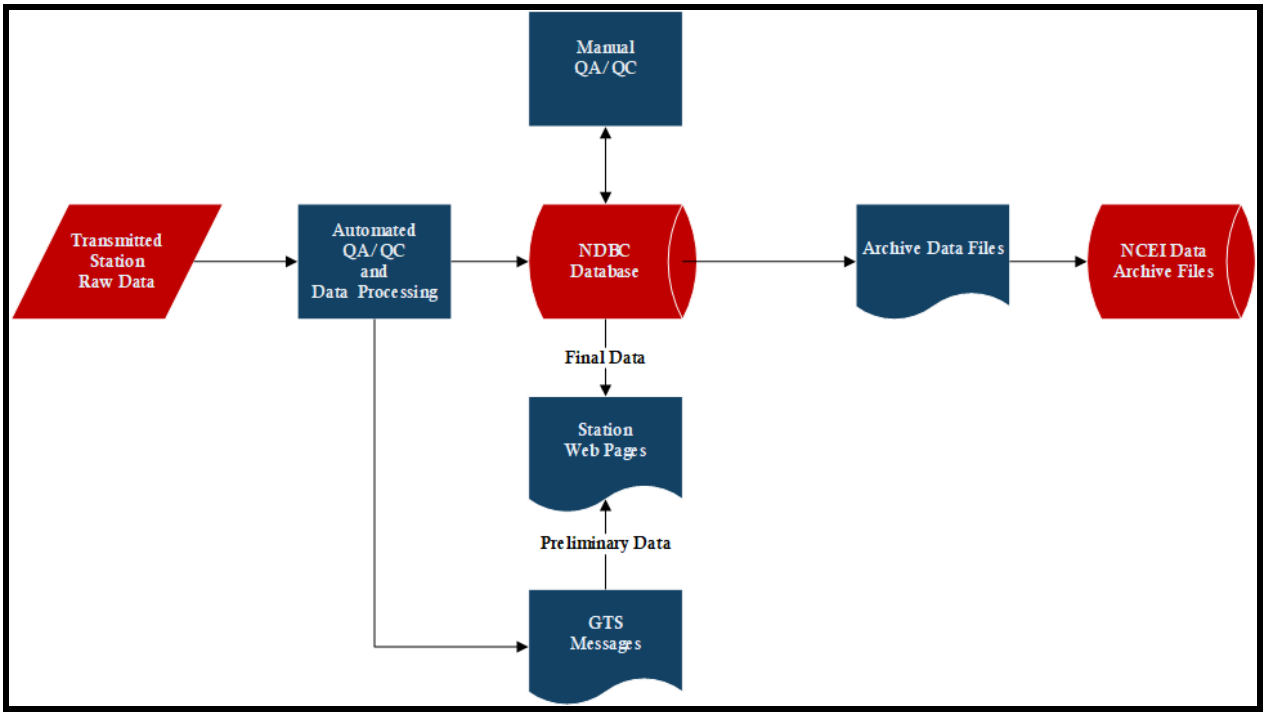

Figure 1: Data flow pathway for Coastal Weather Buoy and C-MAN stations from receipt of transmitted observation to permanent archive.

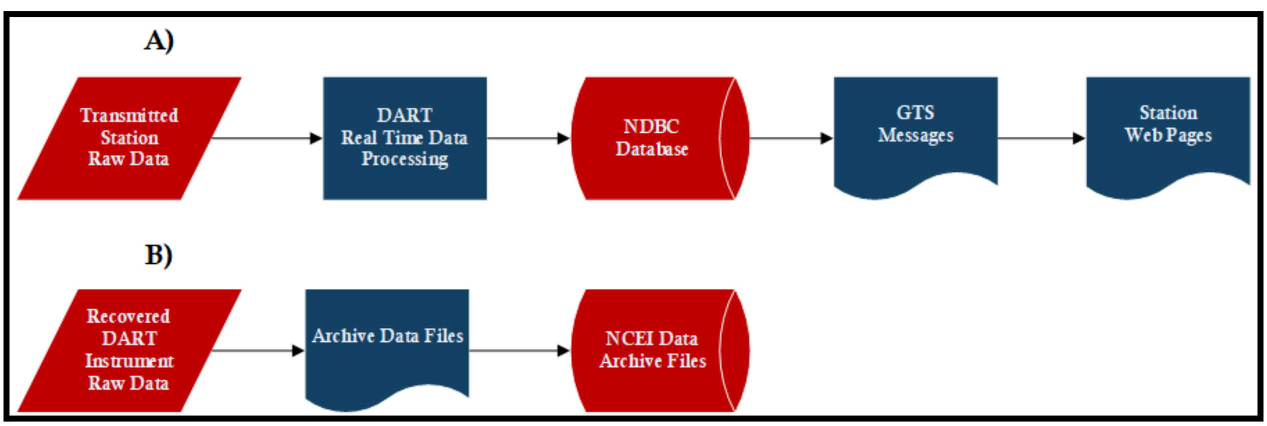

Figure 2: Data flow pathway for DART stations from A) receipt of transmitted real-time observation to NDBC website, and B) recovered logged instrument data to permanent archive.

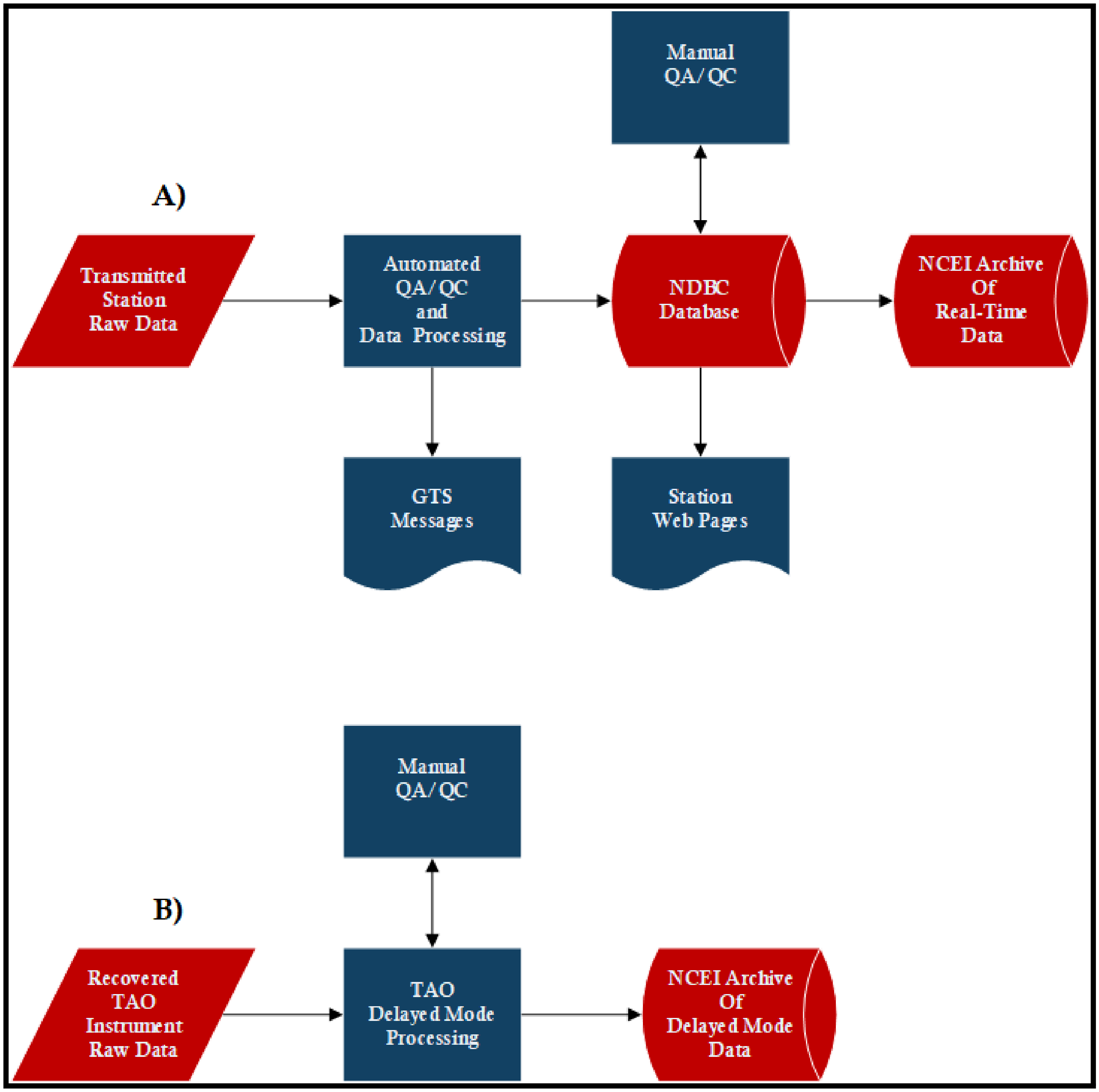

Figure 3: Data flow pathway for TAO stations from A) receipt of transmitted real-time observation and B) recovered logged instrument data to permanent archive.

Once the telemetered raw data is received shoreside, all observations except DART undergo automated QC checks. For Coastal Weather Buoy, C-MAN, and TAO, the data are then stored in the NDBC database and simultaneously formatted for real-time release to the Global Telecommunication System (GTS)[1]. For DART stations, the data are first stored in the NDBC database and then formatted for real-time release to the GTS.

Quality control for real-time data is a two-step process for Coastal Weather Buoy, C-MAN, and TAO. The first steps are the automated QC checks that occur when the raw data are received

[1] https://public.wmo.int/en/programmes/global-telecommunication-system

shoreside. Following the automated QC, a preliminary version of the data is made available on the website in real-time. The second step is manual QC performed by data analysts after data is stored in the database. This step occurs after GTS release and population of the website. After manual QC, the website is updated with the final version of the data.

The quality control for the delayed mode data relies on post-processing by the data analyst. It is a combination of scripted QC algorithms and manual inspection of the data.
Real-time data from DART buoys do not undergo quality control. The website is updated with data after real-time release to the GTS.

Archival of Coastal Weather Buoy and C-MAN data occurs after real-time release and quality control is performed. Archival of TAO and DART data occurs after recovery of the logged observation on the deployed equipment, and quality control is performed. All official records are stored at NCEI.

3. NDBC OBSERVATIONS

A brief description of NDBC observations and the associated sensors and techniques used to make these observations are given in this section. The following subsections describe the specific types of sensors used to collect the observations and their basic principles of operation.

The standard suite of observations on NDBC Coastal Weather Buoys includes winds, atmospheric pressure, air temperature, water temperature, and waves. The majority of buoys also measure relative humidity and dew point temperature. All C-MAN sites measure winds, atmospheric pressure, and air temperature. Most C-MAN sites measure relative humidity and dew point temperature, and a few measure water temperature. The NDBC DART network consists exclusively of tsunameters that measure water-column height based on seafloor hydrostatic pressure. For TAO buoys, standard measurements include winds, air temperature, relative humidity, sea surface and subsurface water temperatures, sea surface salinity, and hydrostatic pressure. Select TAO buoys also measure solar radiation, rain rate, atmospheric pressure, subsurface salinity, and ocean currents.

Some NDBC stations have redundant sensors. When a station has two sensors reporting redundant observations, one of the sensors is chosen as the primary sensor and released to the GTS and website in real-time. The other is designated as the backup or secondary sensor and only released to the GTS and website in the event of a failure of the primary sensor. However, all observations collected by all sensors are archived at the NOAA official archive center.

The sampling scheme used by NDBC is related to the observing network, the data acquisition system, and type of observation. Table 2 shows the current reporting interval and averaging duration for each observation on NDBC-operated platforms and systems. At present, NDBC stations operate with a variety of DAS; for example, Coastal Weather Buoys utilize the Self-Contained Ocean Observing Payload (SCOOP), as well as older Legacy DAS. All NDBC observations are time stamped at the end of the acquisition interval or after the end of the acquisition. The sampling frequency of each sensor on the Coastal Weather Buoy, C-MAN, and TAO arrays are available at the following links on the NDBC website:

- Coastal Weather Buoy & C-MAN: https://www.ndbc.noaa.gov/faq/rsa.shtml
- TAO: https://tao.ndbc.noaa.gov/proj_overview/sampling_ndbc.shtml

There are exceptions to the standard sampling and reporting scheme as given in Table 2. For the Coastal Weather Buoy and C-MAN networks, a small number of stations collect observations at a higher frequency, depending on the needs of the primary stakeholders. The DART network is designed to transmit observations more frequently when a water column variation is detected. The only difference with the TAO array is the acquisition time stamp, where the TAO daily averages are time stamped at the middle of the acquisition interval.

Table 2. Sampling scheme by network and data acquisition system

Observation	**Network**					
	TAO	Coastal Weather Buoy		C-MAN		DART
		Legacy	SCOOP	Legacy	SCOOP	
Atmospheric Pressure	2-minute average (1/hour)	8-minute average (1/hour)	1-minute average (6/hour)	2-minute average (1/hour)	1-minute average (6/hour)	N/A
Wind Direction	2-minute average (6/hour)	8-minute average (1/hour)	10-minute average (6/hour)	2-minute average (1/hour)	10-minute average (6/hour)	N/A
Wind Speed	2-minute average (6/hour)	8-minute average (1/hour)	10-minute average (6/hour)	2-minute average (1/hour)	10-minute average (6/hour)	N/A
Air Temperature	2-minute average (6/hour)	8-minute average (1/hour)	10-minute average (6/hour)	2-minute average (1/hour)	10-minute average (6/hour)	N/A
Dew Point	2-minute average (6/hour)	8-minute average (1/hour)	10-minute average (6/hour)	2-minute average (1/hour)	10-minute average (6/hour)	N/A
Rain	10-minute average (6/hour)	N/A	N/A	N/A	N/A	N/A
Short Wave Radiation	2-minute average (30/hour)	N/A	N/A	N/A	N/A	N/A
Long Wave Radiation	2-minute average (30/hour)	N/A	N/A	N/A	N/A	N/A
Wave Height	N/A	20-minute average (1/hour)	20-minute average (2/hour)	N/A	N/A	N/A
Wave Period	N/A	20-minute average (1/hour)	20-minute average (2/hour)	N/A	N/A	N/A

Observation	Network					
	TAO	Coastal Weather Buoy		C-MAN		DART
		Legacy	SCOOP	Legacy	SCOOP	
Wave Direction	N/A	20-minute average (1/hour)	20-minute average (2/hour)	N/A	N/A	N/A
Sea Surface Water Temperature	Instantaneous (6/hour)	8-minute average (1/hour)	Instantaneous (6/hour)	2-minute average (1/hour)	N/A	N/A
Subsurface Water Temperature	Instantaneous (6/hour)	N/A	N/A	N/A	N/A	N/A
Salinity	Instantaneous (6/hour)	N/A	N/A	N/A	N/A	N/A
Water Pressure (mooring line)	Instantaneous (6/hour)	N/A	N/A	N/A	N/A	N/A
Water pressure (seafloor)	N/A	N/A	N/A	N/A	N/A	15-sec average (4/hour)
Ocean Current (Point)	2-minute average (1/hour)	2.5-minute average (2/hour)	5-minute average (6/hour)	N/A	N/A	N/A
Ocean Current (Profile)	6-minute average (1/hour)	N/A	N/A	N/A	N/A	N/A

3.1. ATMOSPHERIC PRESSURE

All NDBC platforms except for DART buoys measure atmospheric pressure by utilizing a digital aneroid barometer or a piezo-resistance silicon resonant sensor. The accuracy of the observation is related to the type of sensor used to collect the measurement. For the Coastal Weather Buoy and the C-MAN networks, NDBC uses the aneroid barometer, and for climate quality observation in the TAO array the higher accuracy silicon resonant sensor is used (refer to Table 1 for specific sensor accuracy). The following pressure measurements are made:

- Air pressure at station level (also known as station pressure) is measured in hectopascals (hPa) by the barometer at the elevation of each sensor.
- Air pressure at sea level (also known as sea level pressure) is the station pressure reduced to sea level in units of hPa. The conversion to sea level pressure is made using the procedures described in the NWS Technical Procedures Bulletin No. 291 (NWS 1980), (NDBC/NTSC 2007), and (WBAN 1964).

Many NDBC Coastal Weather Buoys and C-MAN stations can be exposed to intense low pressure systems that can result in severe weather events. As a result, NDBC has the capability to measure and report 1-minute average air pressure data as recorded at sea level. The supplemental pressure data are as follows:

- The lowest measured air pressure for the hour is called minimum 1-minute air pressure.
- The time that the minimum 1-minute air pressure is reported as the minute within the hour that this observation occurred.

3.2. WIND MEASUREMENTS

Wind observations are collected on all NDBC stations with the exception of the DART network. The accuracy of the observation is related to the type of sensor used to collect the measurement (refer to Table 1). For the SCOOP Coastal Weather Buoy and C-MAN stations, the primary wind sensor is an impeller-driven wind-vane anemometer and the secondary wind measurements are collected with an all-in-one instrument that utilizes a sonic anemometer. For the Legacy Coastal Weather Buoy and C-MAN stations, the primary and secondary wind sensors are impeller-driven wind-vane anemometers. The TAO array climate quality wind data are collected with a single impeller-driven wind-vane anemometer. The following base wind measurements are made on NDBC stations:

- Wind direction is the direction from which the wind is blowing in degrees clockwise from true north for Coastal Weather Buoy and C-MAN. For TAO, the wind direction is the direction the wind is blowing toward in degrees clockwise from true north.
- Wind speed is reported in meters per second (m/s).

In addition, wind gusts from Coastal Weather Buoy and C-MAN stations are reported in meters per second (m/s).

The wind direction is a unit vector average, whereas the wind speed is a scalar average. The wind gust is the highest wind speed measured in the sampling period. It is calculated from the highest 5-second running mean during the sampling period.

Although Coastal Weather Buoys and C-MAN stations with Legacy systems generally only report once per hour, they have the capability to continuously sample the winds. Continuous wind data on these stations are reported each hour in six 10-minute intervals. At the end of each hour, the following measurements are reported by the payload:

- Continuous wind speed: The mean wind speed (m/s) reported by the anemometer during each 10-minute period.
- Continuous wind direction: The mean unit vector wind direction, in degrees relative to true north during each 10-minute period.
- Hourly max gust: The maximum 5-second wind speed (m/s) reported during the hour.
- Direction of hourly max gust: The direction (in degrees true) associated with the hourly max gust.

Coastal Weather Buoys and C-MAN stations also report the wind speed adjusted to 10 m and 20 m above the site elevation. These values are derived from an algorithm as given by Liu et al. (1979). See Section 5.2 for further details.

Coastal Weather Buoys that are climatologically in the path of hurricanes or other intense storms have the capability to report the maximum 1-minute wind speed recorded during the sampling interval. On Coastal Weather Buoys and C-MAN stations with Legacy DAS, the direction associated with the maximum 1-minute wind speed is also reported. This capability will be implemented on SCOOP payloads in the future.

3.3. AIR TEMPERATURE

Air temperature observations are collected on all NDBC stations with the exception of the DART network. The accuracy of the observation is related to the type of sensor used to collect the measurement (refer to Table 1). All NDBC air temperature sensors are analog thermistors, and are either a stand-alone sensor or are part of an integrated weather system package. The following air temperature observation is made on NDBC stations:

- Air temperature is measured in degrees Celsius.

All Legacy Coastal Weather buoys have a redundant air temperature sensor, yet only a portion of the Legacy C-MAN stations have a redundant air temperature sensor. Coastal Weather Buoys and C-MAN stations with SCOOP systems, as well as TAO buoys, do not have a redundant air temperature sensor.

3.4. RELATIVE HUMIDITY/DEW POINT TEMPERATURE

Relative humidity observations are directly measured on all TAO stations and most Coastal Weather Buoy and C-MAN stations. Relative humidity is not measured on the DART network. Dew point temperature is a derived observation that is calculated on Coastal Weather Buoys and C-MAN stations that have relative humidity observations. The accuracy of the observation is related to the type of sensor used to collect the measurement (refer to Table 1). The humidity sensors used by all NDBC stations are resistive hygrometers that calculate the atmospheric water vapor pressure. The instrument includes a temperature probe to provide a temperature correction in the calculation of all relative humidity observations. The following humidity observations are made on NDBC stations:

- Relative humidity is the atmospheric water vapor pressure divided by the saturation water vapor pressure, expressed as a percentage.
- Dew point temperature is the temperature to which the air would have to be cooled for saturation to occur.

The sampling period is a function of the payload (Table 2). All TAO stations release relative humidity in real-time to the website and GTS, and as a delayed mode observation to the archive center. Coastal Weather Buoys and C-MAN stations report dew point temperature as a real-time observation on the website and the GTS. In addition to dew point temperature, the Coastal Weather Buoys and some C-MAN stations also archive relative humidity.

3.5. RAIN

Rain is the only form of precipitation measured only on some TAO buoys. NDBC uses a siphoning precipitation gauge to directly measure the rain level and from this value a derived rain rate is calculated. The accuracy of the precipitation measurement is given in Table 1. The following data are provided by the rain gauges:

- Rain rate: The amount of rainfall observed per unit time, in units of mm/hr.

3.6. SHORTWAVE RADIATION MEASUREMENTS

Shortwave, or solar, radiation is defined as downwelling ultraviolet, visible, and near-infrared radiation. It is only measured on TAO buoys.Shortwave radiation is measured using a temperature compensated pyranometer. The accuracy of the observations is given in Table 1. The following measurement is made by the pyranometer:

- Shortwave Radiation is the actual measurement in units of W/m^2.

3.7. LONGWAVE RADIATION MEASUREMENTS

Longwave, or terrestrial, radiation is defined as downwelling infrared radiation. It is only measured on TAO buoys. Longwave radiation is measured using a temperature compensated pyrgeometer. The accuracy of the observations is given in Table 1. The following measurement is made by the pyrgeometer:

- Longwave Radiation is the actual measurement in units of W/m^2.

3.8. OCEAN WAVE MEASUREMENTS

Wave measurements are only collected on Coastal Weather Buoys. NDBC collects wave observations using a three-axis motion sensor integrated with a magnetometer located in the center of the buoy near the water line. The ocean wave observations are derived from a time series of buoy heave, pitch, roll and azimuth. From the time series measurements NDBC derives the spectral wave observations. The bulk wave parameters are then derived from the spectral wave data. For complete details on NDBC wave processing, refer to NDBC Technical Document 03-01.

The time series measurements are used to derive the following spectral parameters:

- Sea surface wave variance spectral density uncorrected (C_{11}^M) is the raw acceleration spectral density for each frequency band, in units of $m^2/s^4/Hz$.
- Sea surface wave variance spectral density (C_{11}) is the total wave energy in each frequency band, in units of m^2/Hz.
- Sea surface wave spectral mean direction (α_1) is the average direction from which the waves are traveling in units of degrees relative to true north for each frequency bin.
- Sea surface wave spectral principal direction (α_2) is the primary direction from which the

waves are traveling in units of degrees relative to true north for each frequency bin.

- Sea surface wave mean spreading coefficient (R_1) is a first-order measure of the directional spread of the mean spectral wave direction. It is a unitless value ranging from 0 to 1, with larger values indicating a tighter distribution of energy around the mean direction.
- Sea surface wave principal spreading coefficient (R_2) is a second-order measure of the directional spread of the principal spectral wave direction. It is a unitless value ranging from 0 to 1, with larger values indicating a tighter distribution of energy around the principal direction.

From these spectral parameters, the following bulk wave parameters are derived:

- Sea surface wave significant height (H_s) is the average height of the highest one third of the waves in units of meters.
- Sea surface wave period at variance spectral density maximum is the dominant or peak wave period (T_p) corresponding to the frequency band with the maximum spectral energy density, in units of seconds.
- Sea surface wave mean period (T_m) is the average period measured over the observation duration, in units of seconds.
- Sea surface wave from direction at variance spectral density maximum is the wave direction corresponding to the frequency band with the maximum spectral energy density, in units of degrees relative to true north.

The accuracy of the bulk wave parameters are related to the type of sensor and the buoy processor (refer to Table 1).

3.9. SEA SURFACE WATER TEMPERATURE

Sea surface temperature (SST) observations are collected on all TAO stations and Coastal Weather Buoys, and some C-MAN stations. SST measurements are not collected on the DART stations. TAO buoys and Coastal Weather Buoys with SCOOP payloads measure sea surface temperatures using an in-situ digital temperature probe mounted to the bridle of the buoy. Whereas, Legacy Coastal Weather Buoys rely on a hull mounted thermistor inside the buoy hull as a proxy for sea surface temperature. The water temperature measurements at C-MAN stations use an analog thermistor probe mounted at fixed distances relative to the bottom; therefore, the observation is at different depths below the ocean surface throughout the day owing to changing water levels. The accuracy of the observation is related to the type of sensor used to collect the measurement (refer to Table 1). The following SST measurements are made on NDBC stations:

- Sea surface temperature is measured in units of degrees Celsius.

3.10. SUBSURFACE WATER TEMPERATURE

Subsurface water temperature observations are only collected on TAO stations. The measurements are collected using an in-situ digital temperature probe mounted to the buoy mooring. The observations are measured at multiple discrete depths ranging from 5 meters down to 500 meters. The sampling depth will vary depending on the location of the station. The accuracy of the observation is related to the type of sensor used to collect the measurement (refer to Table 1). The following subsurface temperature measurements are made on TAO stations:

- Subsurface temperatures at various depths are measured in units of degrees Celsius.

3.11. SEA SURFACE SALINITY

Sea surface salinity (SSS) observations are standard on every TAO buoy, but not collected on other NDBC observing systems. Sea surface salinity observations are derived from measurements of temperature and conductivity located in the buoy bridle approximately 1 meter below the sea surface. NDBC uses an electrical conductivity sensor that is coupled with a thermistor probe to calculate sea surface salinity. The accuracy of the observation is related to the type of sensor (refer to Table 1). The following observations are available:

- Salinity is unitless but expressed in terms of practical salinity units (psu)
- Conductivity in units of siemens per meter (S/m)
- Density (sigma-theta) in units of kilograms per cubic meter (kg/m^3)

All TAO buoys release salinity in real-time and as a delayed mode observation. However, density is only available as a delayed mode observation and conductivity is only available in real-time.

3.12. SUBSURFACE SALINITY

Subsurface salinity observations are available on select TAO buoys, but not collected on other NDBC observing systems. Subsurface salinity observations are derived from temperature and conductivity measurements located at discrete locations along the mooring line from depths of 5-125 meters. NDBC uses an electrical conductivity sensor that is coupled with a thermistor probe to calculate subsurface salinity. The accuracy of the observation is related to the type of sensor (refer to Table 1). The following observations are available:

- Salinity in units of practical salinity units (psu)
- Conductivity in units siemens per meter (S/m)
- Density (sigma-theta) in units of kilograms per cubic meter (kg/m^3)

All TAO stations release salinity in real-time and as a delayed mode observation. However, density is only available as a delayed mode observation and conductivity is only available in real-time.

3.13. WATER PRESSURE

Water pressure observations are collected only on TAO and DART buoys and not on Coastal Weather Buoys or C-MAN stations. For the TAO array, the water pressure measurements are collected by sensors located on the mooring line at depths of 300 and 500 meters. TAO uses a strain-gauge pressure sensor embedded in the temperature sensor. The following measurement is made on TAO buoys:

- Water pressure is the actual measurement in units of decibars.

The DART network collects a seafloor water pressure measurement on an ocean bottom-mounted platform. The accuracy of the observation is related to the type of sensor (refer to Table 1). DART stations use a temperature compensated quartz resonance pressure gauge.

For DART stations, the water pressure measurement is converted to water column height observation. The following measurements are made for DART:

- Water column height is the derived observation in units of meters.

All DART stations measure and transmit water column height in meters in real-time, yet the delayed mode data is recorded as pounds per square inch (psi).

3.14. OCEAN CURRENT MEASUREMENTS

Ocean current measurements are collected on TAO stations and select NDBC Coastal Weather Buoys, but not on C-MAN or DART stations. NDBC collects both point and profile current measurements. The point current measurements are collected by sensors on the mooring line at four or five locations from depths of 10 to 200 meters. Whereas, the current profile ranges from the near surface depth of approximately 30 meters down to a maximum depth of 300 meters. NDBC uses acoustic instruments for both the point measurements and the profiles. The accuracy of current observations are related to the type of sensor (refer to Table 1). The following observations are available:

- Current speed reported in centimeters per second (cm/s).
- Current direction in degrees clockwise from true north in the oceanographic direction.
- Current velocity components *u*, *v*, and *w* are reported in centimeters per second (cm/s).

All TAO stations release point current measurements speed and direction in real-time to the GTS and the website, and as a delayed mode observation to the archive center. However, the vertical component of point current velocity is only available in real-time. The current profile measurements are only available as vector components as a delayed mode observation.

4. <u>QUALITY ASSURANCE</u>

NDBC performs testing at various stages to ensure that quality data are reported from our systems of record. The various techniques to ensure data quality are described in this section.

4.1. UNIT LEVEL TESTING

NDBC employs a mixture of in-house testing and vendor-performed testing on the sensors used to collect observations. The in-house and vendor-performed testing verifies that the sensor operates within its acceptable range. All sensors go through a physical inspection and a unit-level verification at NDBC. Test equipment used to verify sensor functionality is calibrated on a regular basis by an independent NIST-traceable laboratory. NDBC test facilities include a wind tunnel, salt bath, humidity chamber, temperature chamber, pressure chamber, compass rose, tri-axis wave simulator, and other general sensor testing.

Calibration coefficients are created from these tests and applied to some sensors. These calibration coefficients are either stored internal to the system/sensor or applied shoreside.

4.2. SYSTEMS TESTING

NDBC systems testing consists of multiple phases at each stage of the integration process. These phases are detailed in the subsections below.

4.2.1. INTEGRATION TESTING

NDBC buoys and systems are assembled from equipment that has been individually tested. Once a system is built, it undergoes a 48-hour verification test at NDBC facilities to ensure that all sensors and telemetry systems are functioning, and that all calibration coefficients and shoreside processing parameters are configured properly. At the conclusion of this 48-hour test, the data are compared against a standard system maintained at the NDBC test facility to ensure that all systems are reporting within accuracy requirements.

4.2.2. RE-ASSEMBLY

After completion of the 48-hour integration test at NDBC, the system is disassembled and the components are packed for shipping. Once a system arrives in port, it is reassembled and powered on, either dockside or on the deck of the servicing vessel.

4.2.3. FIELD VERIFICATION

After a system is shipped, reassembled, and powered up, data are compared against a local standard for three hours to ensure proper operation of all sensors and telemetry systems. Once the data are verified, the system enters a 12-hour field verification to ensure that all components continue to function as expected. When the field verification is complete, the system is ready to be deployed.

4.3. DEPLOYMENT VERIFICATION

Upon deployment, the data are compared against independent observations in the field for three hours. If any discrepancies occur during this time, the system is repaired on scene and the verification is restarted. The technicians depart the station upon completion of three hours of successful verification.

5. DATA PROCESSING

To ensure the highest quality observations, adjustments may be applied to the raw data received at NDBC. The type of adjustment is dependent on the sensor and/or payload type. Some adjustments are applied onboard while other adjustments are applied after the data are received by NDBC. In general, onboard adjustments are restricted to magnetic anomalies and hull response. The various adjustments to the data are described in the subsections below.

Some data are derived using more than one measurement. Relative humidity and salinity are examples of derived observations. The derived observations are also described in the subsections below.

5.1. ATMOSPHERIC PRESSURE

TAO buoys and Coastal Weather Buoys with Legacy systems measure atmospheric pressure from a hull-mounted sensor located near sea level. However, Coastal Weather Buoys in the Great Lakes and most C-MAN stations are located above sea level, and therefore require an adjustment to the atmospheric pressure data. The adjustment to sea level pressure is performed using the procedures described in the NWS Technical Procedures Bulletin No. 291 (NWS 1980). On Coastal Weather Buoys with SCOOP systems, the atmospheric pressure sensors are located on the buoy mast, which necessitates a small height adjustment. All corrections to atmospheric pressure data are performed shoreside.

5.2. WIND MEASUREMENTS

Wind directions on Coastal Weather Buoys and TAO stations are measured relative to the buoy heading, and are adjusted using the compass heading to obtain the wind direction relative to magnetic north. This adjustment is performed on board the buoy. An additional adjustment is performed shoreside to correct for the variation between magnetic and true north. C-MAN station winds are mechanically aligned toward true north, and therefore do not require adjustment. No shoreside calibration coefficients are applied to Coastal Weather Buoys or C-MAN stations.

Sensor calibration coefficients are applied shoreside for both wind speed and direction on TAO buoys. The calibrated wind speed and direction are then used to derive the zonal and meridional components of the wind.

On Coastal Weather Buoys and C-MAN stations, the wind speeds at 10 m and 20 m above ground are calculated using the algorithm described by Liu et al. (1979). NDBC applies the adjustment using the measured wind speed and anemometer height, the measured air and water temperature, a constant 85% relative humidity, and a constant 1013.25 hPa sea level pressure. If either the air or water temperature is unavailable, then neutral boundary layer stability is assumed. For more details, refer to Liu et al. (1979).

5.3. AIR TEMPERATURE

Sensor calibration coefficients are applied shoreside for air temperature measurements on TAO buoys. Coastal Weather Buoys and C-MAN stations report the raw measurements from the sensor with no calibration applied.

5.4. HUMIDITY AND DEW POINT

The processing algorithms for humidity and dew point temperature vary greatly depending on the system, platform and payload type.

5.4.1. <u>TAO Buoys</u>

TAO buoys transmit raw measurements for relative humidity, which are adjusted using shoreside calibration coefficients obtained during sensor testing. The calibrated relative humidity measurements are reported in real-time and archived data. No conversion to dew point temperature is performed. Figure 4 below shows the processing flow of humidity data on TAO systems.

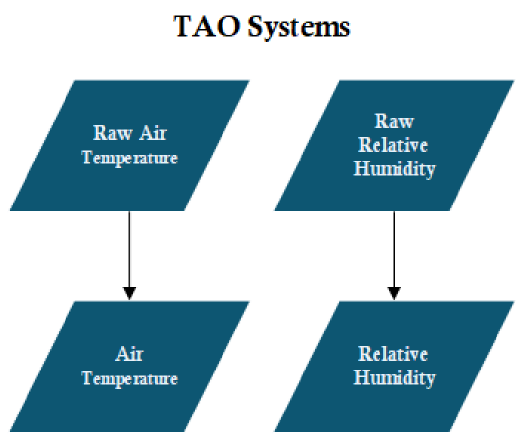

Figure 4: Data flow processing flowchart for TAO relative humidity data.

5.4.2. <u>Coastal Weather Buoy and C-MAN Stations</u>

Shoreside processing for humidity and dew point temperature on Coastal Weather Buoys and C-MAN stations differs for each payload type, since each payload transmits different raw measurements. The equations to convert between relative humidity and dew point temperature are given in Appendix A, and are consistent across all payload types.

SCOOP systems contain a single all-in-one meteorological sensor, which reports both air temperature and relative humidity. The relative humidity measurements are adjusted using shoreside calibration coefficients. The air temperature and adjusted relative humidity are then used to calculate the dew point temperature. Figure 5 below shows the processing flow of humidity data on SCOOP systems.

5.4.2.1. SCOOP Payloads

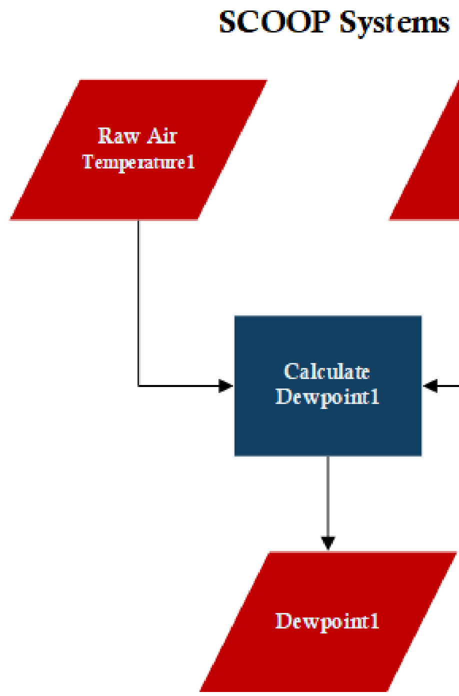

Figure 5: Data flow processing flowchart for relative humidity and dew point data on SCOOP payloads.

Legacy AMPS, ARES, and Sutron payloads contain a standalone air temperature sensor, which reports the #1 air temperature measurement, and a combined air temperature and humidity sensor, which reports the #2 air temperature measurement and the relative humidity. No shoreside calibration is performed on any of the raw measurements. The #2 air temperature and relative humidity are used to calculate the #2 dew point temperature, and the #1 air temperature and relative humidity are used to calculate the #1 dew point temperature. Finally, the relative humidity is recalculated using the #1 air temperature and the #1 dew point temperature. Figure 6 below shows the processing flow of humidity data on Legacy systems (ARES and Sutron).

5.4.2.2. AMPS, ARES, and Sutron Payloads

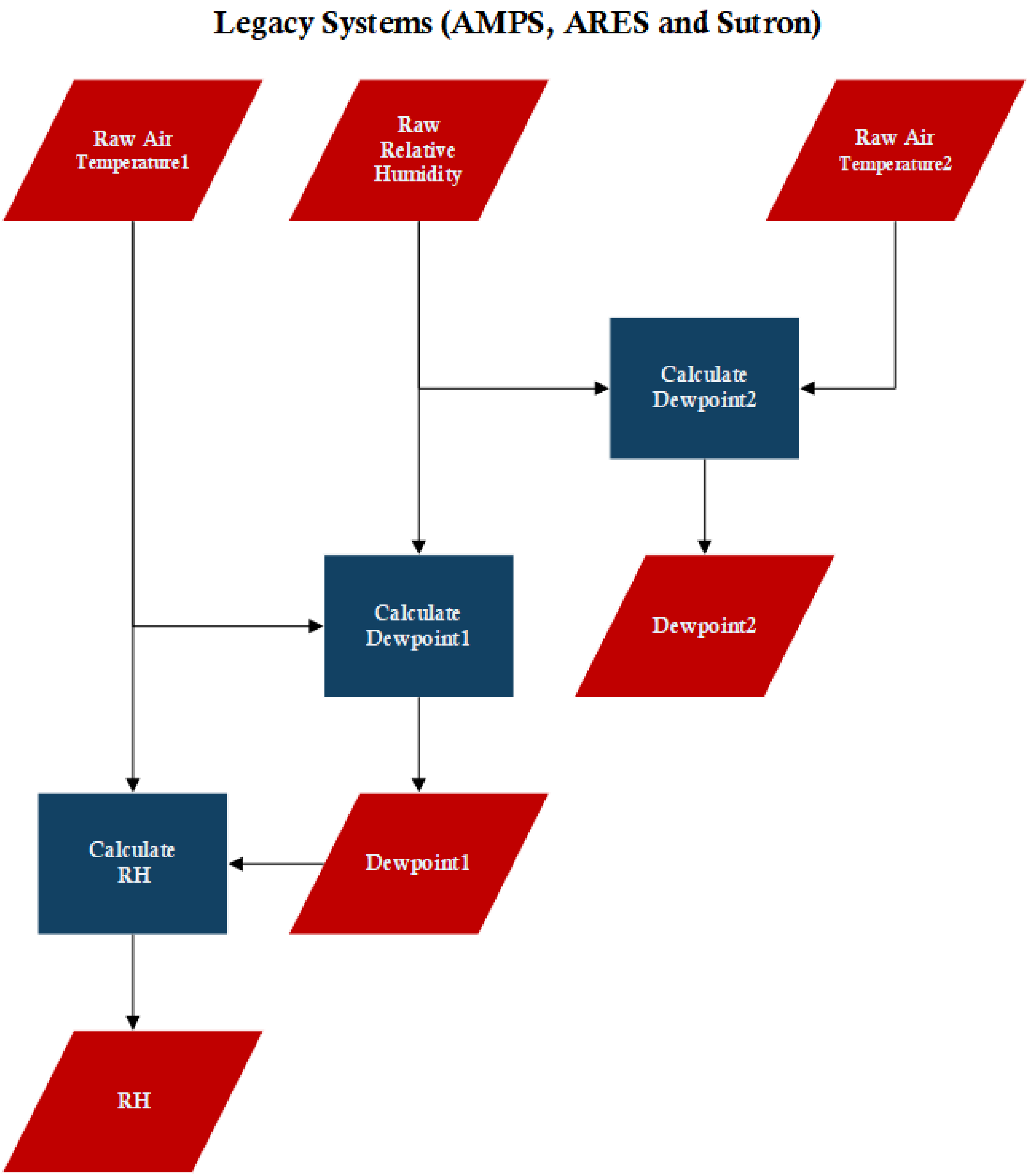

Figure 6: Data flow processing flowchart for relative humidity and dew point data on AMPS, ARES and Sutron payloads.

5.4.2.3. MARS Payloads

MARS payloads have separate sensors that report air temperature and dew point. No shoreside calibration coefficients are applied to either measurement. Relative humidity is calculated shoreside from these two measurements. Figure 7 below shows the processing flow of humidity data on Legacy MARS systems.

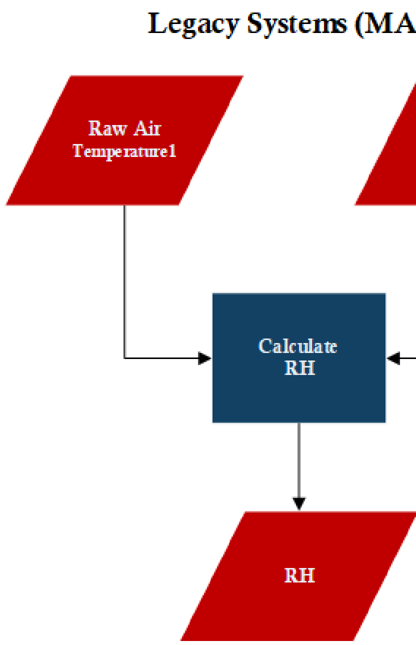

Figure 7: Data flow processing flowchart for relative humidity and dew point data on MARS payloads.

5.5. RAIN

TAO buoys report once-per-minute measurements of the volume of water in the rain gauge. The algorithm for shoreside processing and quality control of this data is summarized in Figure 8.

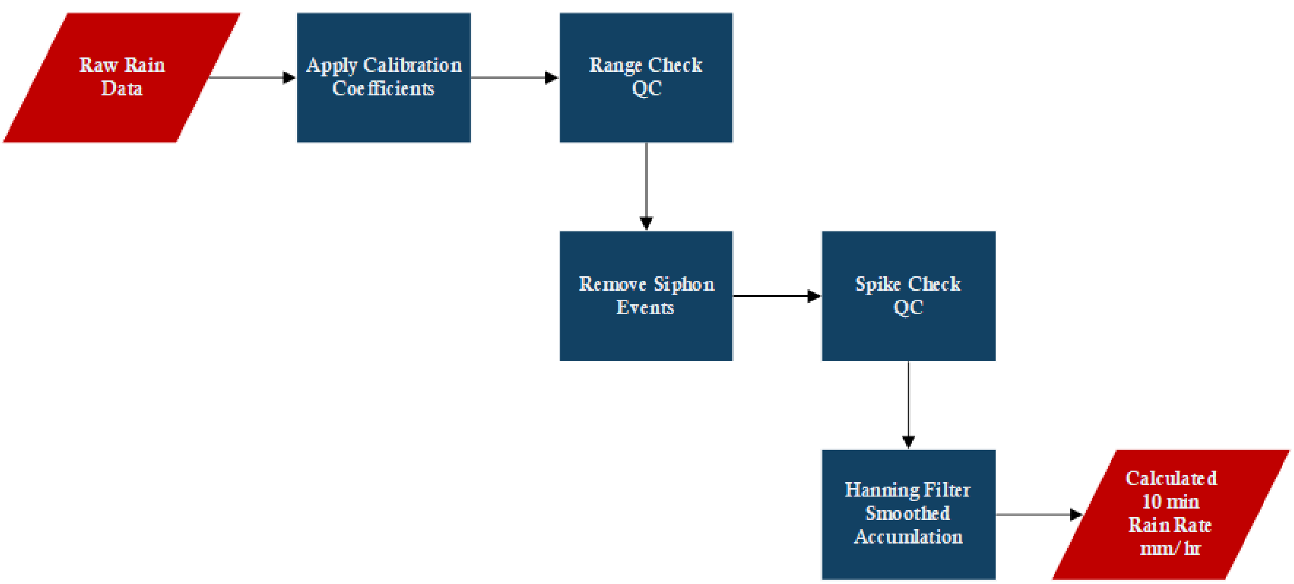

Figure 8: Data flow processing flowchart for TAO rain data.

The first step in the shoreside processing algorithm is to apply shoreside calibration coefficients to the raw measurements. After a gross range check in which unrealistic measurement values are discarded, siphon events are removed by subtracting the water level at the beginning of the deployment and re-adding any water drained during siphon events. This results in the calculation of total accumulation. Next, a spike check is performed on the accumulation data, and a 16-point Hanning cosine filter is applied to smooth out high-frequency noise. Finally, the rain rate is calculated based on the 10-minute change in the filtered accumulation.

5.6. SHORTWAVE RADIATION

TAO buoys report raw shortwave radiation sensor counts. A set of generic coefficients is applied by the payload to calculate the shortwave radiation in units of W/m^2. The measurements are further adjusted shoreside using a set of sensor-specific calibration coefficients.

5.7. LONGWAVE RADIATION

TAO buoys report raw sensor counts for thermopile radiation, case temperature, and dome temperature. The shoreside processing algorithm applies the sensor-specific calibration coefficients to the thermopile radiation and case temperature to calculate the final longwave radiation measurement. The equations used in these calculations are shown in Appendix A.

5.8. OCEAN WAVE MEASUREMENTS

Wave observations are taken on all NDBC Coastal Weather Buoys. A brief summary of the process of deriving a wave observation is given below. For complete details on NDBC wave processing algorithms and a description of all spectral wave parameters, refer to NDBC Technical Document 03-01.

NDBC buoys measure time series of pitch, roll, heave, and azimuth. A Fast Fourier Transform (FFT) is performed on these time series to derive spectral wave parameters. The spectral data are adjusted to account for low-frequency electronic noise. In addition, a phase lag correction and response amplitude operator are applied to the spectral data to account for the response of the hull to the motion of the water surface. Finally, the adjusted spectral data are used to derive the bulk wave parameters. Below is an example spectrum (Figure 9), followed by brief descriptions of how each bulk wave parameter is calculated from the spectrum. Refer to Appendix A for the full equations.

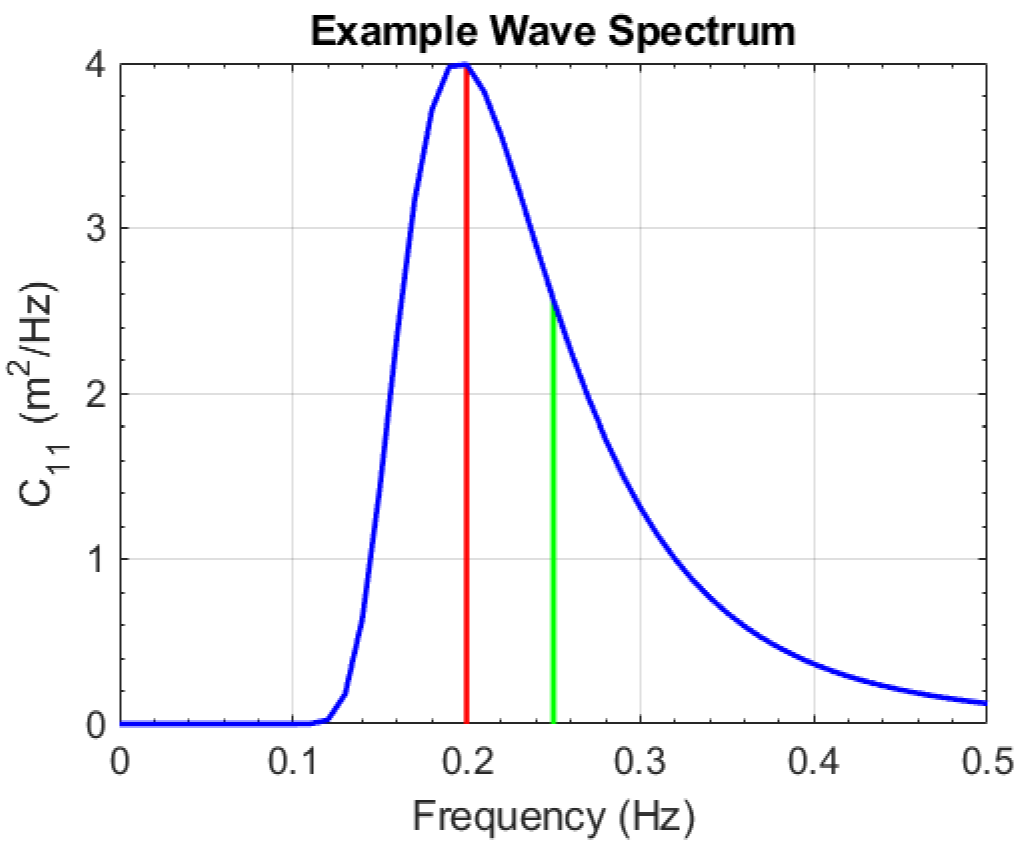

Figure 9: Idealized wave spectrum (blue line) showing the dominant (red line) and average (green line) wave periods.

5.8.1. Significant Wave Height

Significant wave height is defined as the average height of the highest one third of the waves. It is calculated by computing the total integrated spectral energy (i.e. the area under the blue line in Figure 9), taking the square root, and multiplying the result by four.

5.8.2. Dominant Wave Period

Dominant wave period is derived by determining the frequency at which the variance spectral density is the highest, indicated by the red line in Figure 9. The dominant wave period is equal to the inverse of this frequency.

5.8.3. Average Wave Period

Average wave period, represented by the green line in Figure 9, is a weighted average based on the second frequency moment of the wave spectrum. It is calculated by computing the total integrated spectral energy, dividing by the second frequency moment, and taking the square root of the result.

5.8.4. Mean Wave Direction

Mean wave direction is defined as the spectral wave direction at the dominant wave period.

5.8.5. Wind/Swell Wave Separation

NDBC uses the wave steepness method to calculate a separation frequency that partitions the wave spectrum into wind and swell components. The steepness method assumes that wind waves are steeper than swells and that the maximum steepness, or ratio of wave height to length, occurs near the peak of wind wave energy in the spectrum. The separation frequency calculation is provided in Appendix A, and the algorithm is explained fully in Gilhousen and Hervey (2001).

Once the separation frequency is calculated, the wave height and period are calculated separately for the wind wave and swell portions of the spectrum, using the same methods described above.

5.9. WATER TEMPERATURE

NDBC reports the raw measurements for all water temperature observations, with no shoreside adjustments or calibration coefficients applied.

5.10. OCEAN SALINITY

TAO buoys transmit raw measurements of water temperature and conductivity. These raw measurements are used to derive salinity shoreside (Figure 10). Salinity and temperature are then used to derive density. Both the salinity and density calculations utilize algorithms described in Unesco (1983).

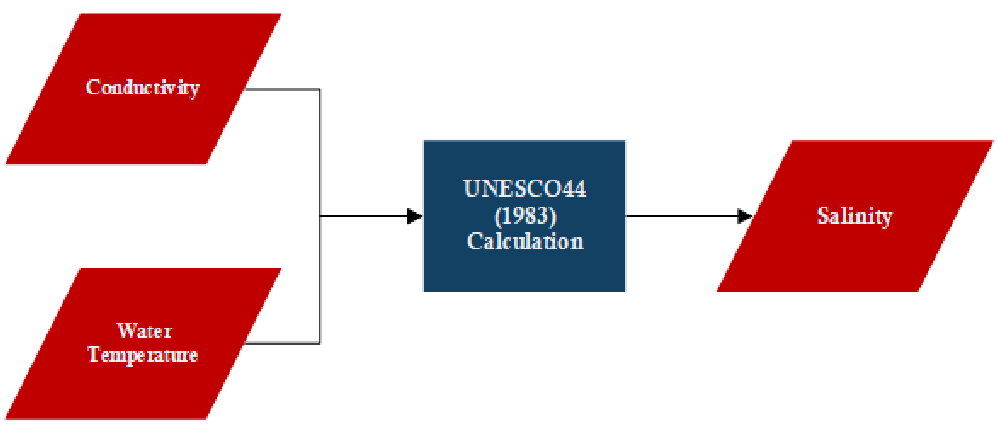

Figure 10: Data flow processing flowchart for salinity data.

5.11. WATER PRESSURE

TAO buoys report water pressure directly measured by the sensor with no adjustments.

DART Bottom Pressure Recorders (BPRs) measure temperature and pressure in units of pounds per square inch absolute (PSIA). The pressure values are corrected for temperature effects. The pressure measurement is converted to an estimated water column height using a constant 670 mm/PSIA. This conversion from pressure to water column height is performed onboard the BPR. The water column height observation is then transmitted shoreside.

5.12. OCEAN CURRENTS

Point current measurements are taken on select buoys in the TAO array and on a few Coastal Weather Buoys. In addition, select TAO buoys also measure ocean current profiles. The data from each of these instruments are processed differently.

5.12.1. Point Source Current Meters

Point source current meters on both Coastal Weather Buoys and TAO buoys report the horizontal current speed and direction. TAO buoys also report the three orthogonal velocity components. These raw values are transmitted in real-time, without any shoreside calibration coefficients or adjustments. A magnetic variation correction is applied to TAO current meter directions prior to final archival at NCEI, and the horizontal velocity components are adjusted accordingly. No magnetic variation correction is performed on current meter data from Coastal Weather Buoys.

5.12.2. Acoustic Doppler Current Profilers

Select TAO buoy locations feature one or more Acoustic Doppler Current Profilers (ADCP), which are attached to the mooring line below the ocean surface and measure current velocities at up to 40 depth bins looking upward through the water column from the instrument. The depths of each bin are then calculated based on the instrument depth and the bin resolution, resulting in a profile of velocity as a function of depth. Since the actual depth of the instrument will vary over time depending on the movement and tautness of the mooring line, an internal pressure measurement is used to determine the depth of the instrument at each measurement time.

6. QUALITY CONTROL ALGORITHMS AND WARNING FLAGS

This section describes the algorithms used to assign QC flags to NDBC measurements. The basic mechanism used to flag a measurement is to compare it with a threshold value which, when exceeded, assigns a flag. Algorithms differ by measurement and by how the thresholds are derived. Some thresholds are fixed, and some are a function of season or location. The various flags and how they should be interpreted are also described.

6.1. QUALITY CONTROL INDICATORS

Each NDBC platform and system has its own set of quality flags. Coastal Weather Buoy and C-MAN use detailed quality flags in addition to the standard numerical flags. DART has no automated quality control flags applied. The flagging schemes for Coastal Weather Buoy, C-MAN, and TAO are described in the sections below.

All detailed quality control algorithms for Coastal Weather Buoy and C-MAN are found in Appendix B, and the corresponding quality control flags are defined in Appendix C. Details on how each quality control algorithm is applied are found in Section 6.2.

6.1.1. Coastal Weather Buoys and C-MAN Stations

Coastal Weather Buoys and C-MAN stations use numerical flags to indicate the data quality, as shown in Table 3:

Table 3: Coastal Weather Buoy and C-MAN Quality Flags

Flag Value	Meaning
1	Good data
2	Quality not evaluated
3	Suspect or high interest
4	Failed
9	Missing

In addition, Coastal Weather Buoys and C-MAN stations use a set of detail flags, indicating which quality control check triggered the flag. The detail flags can either be upper-case letters, lower-case letters, or asterisks. Upper-case letter flags are referred to as “hard” flags, which correspond to a numerical flag value of 4 (failed) and prevent real-time release of the observation. The exception to the above rule is the “M” flag, which corresponds to the numerical flag value of 9 (missing). Lower-case letter flags, or “soft” flags, correspond to a flag value of 3 (suspect or high interest), and do not stop real-time release of the data. Asterisk (*) flags indicate that the observation was initially released in real-time, but was later failed manually by NDBC.

6.1.2. TAO Stations

TAO stations use numerical flags similar to the Coastal Weather Buoys and C-MAN stations to indicate data quality, but with slightly different interpretations of the numerical flag values. The numerical flags used in TAO are described in Table 4.

Table 4: TAO Quality Flags

Flag Value	Meaning
0	Unknown
1	Good data
2	Probably good data
3	Questionable data
4	Bad data
5	Adjusted
9	Missing

Table 5. List of quality control algorithms used by NDBC.

Algorithm	Applicable Platforms and systems
Transmission Quality Check	Coastal Weather Buoy, C-MAN, TAO, DART
Range Check	Coastal Weather Buoy, C-MAN, TAO, DART
Time Continuity Check	Coastal Weather Buoy, C-MAN, TAO
Model Comparison Check	Coastal Weather Buoy, C-MAN
Duplicate Sensor Checks	Coastal Weather Buoy, C-MAN
Related Measurement Check	Coastal Weather Buoy, C-MAN
Battery Voltage Check	Coastal Weather Buoy, C-MAN
Dew Point - Air Temperature Check	Coastal Weather Buoy, C-MAN
Standard Wind Checks ● Wind Direction vs. Buoy Azimuth ● Wind Gust Ratio Check ● Stuck Compass Check	 Coastal Weather Buoy Coastal Weather Buoy, C-MAN Coastal Weather Buoy
Continuous Wind Checks ● Standard vs. Continuous Wind Check ● Standard Deviation Check ● Continuous Wind Related Measurement Check	 Coastal Weather Buoy, C-MAN Coastal Weather Buoy, C-MAN Coastal Weather Buoy, C-MAN
Wave Checks ● Wave Heave Consistency Check ● Wind-Wave Check ● Calm Sea Check ● Spectral Wave Direction Validation ● Wave Height vs. Period Check ● Spectral Wave C11 Spike Check ● Wave vs. Wind Direction Check	 Coastal Weather Buoy Coastal Weather Buoy Coastal Weather Buoy Coastal Weather Buoy Coastal Weather Buoy Coastal Weather Buoy Coastal Weather Buoy
Supplemental Measurement Checks ● 1-Minute Pressure Consistency Check ● 1-Minute Wind Consistency Check	 Coastal Weather Buoy Coastal Weather Buoy
Rain Spike Check	TAO
Repeated Value Check	TAO

6.2. AUTOMATED QUALITY CONTROL ALGORITHMS

The real-time QC algorithms performed for each NDBC platform and system are listed in Table 5. The subsections below provide a basic description of each algorithm, in the same order that they are listed in the table. The mathematical details of the most complex algorithms are further described in Appendix B. NDBC adheres to the community accepted standards of real time quality control as maintained by the Quality Assurance/Quality Control of Real Time Oceanographic Data (QARTOD) project. Many of the NDBC quality control algorithms described in this section are adapted from the applicable QARTOD manuals.

All of the automated checks that assign hard flags are performed prior to the data being released to the GTS and NDBC website. However, the comparison of NDBC measurements against National Centers for Environmental Prediction (NCEP) model data is performed in post-real-time after the model data are ingested into the NDBC database.

6.2.1. Transmission Quality

Coastal Weather Buoys and C-MAN stations with SCOOP payloads, as well as TAO and DART buoys have a checksum at the end of the message that is verified during shoreside processing. If the checksum is missing or does not verify, the message is discarded (TAO, Coastal Weather Buoy, & C-MAN) or the observations are excluded from real-time release (DART).

C-MAN stations that transmit over Geostationary Operational Environmental Satellite (GOES) do not utilize checksum verification, and so the data extraction routines will attempt to decode all available data in the message. Continuous wind and wave observations each undergo additional parity checks. If the spectral wave data is incomplete, the wave height is assigned a **W** flag and is not released. If a single error exists in the continuous winds portion of the message, the affected measurement receives a **T** flag and the other continuous wind measurements receive soft **j** flags. If more than one error exists, all continuous wind measurements are assigned a **T** flag.

6.2.2. Range Check

The range check compares a measurement with pre-established upper and lower limits. If the measurement falls outside of these limits, it will be flagged and excluded from real-time release. The default limits are shown in Table 6, and are based on a combination of sensor reporting ranges and climatological extremes from the U.S. Navy Marine Climatic Atlas (NMCA). NDBC has the ability to adjust these limits on a station-by-station basis if deemed necessary. Coastal Weather Buoys and C-MAN stations that fail the range check are assigned an **L** flag.

Coastal Weather Buoys, C-MAN stations, and TAO buoys undergo an additional range check in which the measurements are compared to climatological limits based on the geographic location and season. This check works in the same way as the standard range check, except that it does not prevent the release of the measurement. Instead, measurements that exceed the climatological limits are assigned warning flags. Coastal Weather Buoy and C-MAN measurements that exceed the lower and upper climatological limits are assigned **a** and **b** flags, respectively.

Table 6. Default Upper and Lower Limit Values.

Parameter	Lower Limit	Upper Limit
Atmospheric Pressure (hPa)	800	1100
Wind Direction (°)	0	360
Wind Speed (m/s)	0	60 (sustained); 72 (gust)
Air Temperature (°C)	-40 (CWxB/C-MAN) -9 (TAO)	40
Dew Point (°C)	-40	40
Relative Humidity (%)	25 (CWxB/C-MAN) 0 (TAO)	102
Precipitation (mm)	-10	60
Shortwave Radiation (W/m^2)	N/A	N/A
Longwave Radiation (W/m^2)	N/A	N/A
Wave Height (m)	0	20
Wave Period (s)	2	26
Wave Direction (°)	0	360
Sea Surface Temperature (°C)	Based on NMCA climatology (CWxB/C-MAN) 5.001 (TAO)	Based on NMCA climatology (CWxB/C-MAN) 40 (TAO)
Subsurface Water Temperature (°C, TAO only)	5.001	40
Salinity (psu)	28	40
Water Pressure (dbar, TAO)	100	725
Water Column Height (m, DART)	-5 m of the mean	+5 m of the mean
Point Source Current Speed (cm/s)	N/A	N/A
ADCP Current (cm/s)	N/A	N/A

Range check for the DART water-column heights is set at ± 5 meters from the mean height. The analysts periodically re-compute the mean height. No soft seasonal limits are applied to the DART range checks.

6.2.3. Time Continuity Check

Time continuity checks track the rate of change over time of an observation and flag the data when the absolute value of the rate of change exceeds a predetermined threshold. NDBC applies two different time continuity checks, one for Coastal Weather Buoys and C-MAN stations, and one for TAO stations.

6.2.3.1. Coastal Weather Buoy & C-MAN

NDBC has derived empirical limits that are used to check the time rate of change of pressure, air temperature, sea surface temperature, wind speed, wave period, wave height, relative humidity, and dew point on Coastal Weather Buoys and C-MAN stations. The time continuity limits for Coastal Weather Buoys and C-MAN stations are defined by a measurement-dependent time continuity parameter, multiplied by 0.58 times the square root of the number of hours elapsed since the previous measurement. The full equation and the theory behind it are explained in Appendix B.

If the change between the latest measurement and the previous measurement exceeds the limit, then the latest measurement is assigned a **V** flag and is not released. A list of default time continuity parameters for each measurement is given in Table 7. These default limits can be adjusted on a station-by-station basis, if necessary.

Table 7. General Values of Time Continuity Parameters

Variable	**Default Time Continuity Parameter**
Sea-Level Pressure (hPa)	21.0
Air Temperature (°C)	11.0
Water Temperature (°C)	8.6
Wind Speed (m/s)	25.0
Wave Height (m)	6.0
Average Wave Period (s)	31.0
Relative Humidity (%)	20.0
Dew Point (°C)	11.0

There are five exceptions to the time continuity test due to the very rapid changes that occur in wind, pressure, air temperature, and wave height during the passage of tropical cyclones and severe extratropical cyclones:

- Air pressure measurements that fail the time continuity check are re-accepted and released if the last two measurements are both less than 1000 hPa.
- Wind speed measurements that fail the time continuity check are re-accepted and released if the air pressure is less than 995 hPa.
- Wind speed measurements that fail the time continuity check are re-accepted and released if they are within 2 m/s agreement with a redundant sensor.
- Air temperature measurements that fail the time continuity check are re-accepted and released if the wind speed is greater than 7 m/s, or if the wind direction has shifted by more than 40° between the last two observations.
- Wave height measurements that fail the time continuity check are re-accepted and released if the wind speed is greater than or equal to 15 m/s.

In addition to the hard time continuity limits described above, NDBC applies more stringent soft limits based on climatological normals for each station's location. These limits are defined as an absolute maximum allowable hourly rate of change, which will trigger an f flag when exceeded. Significant wave height uses a separate soft time continuity limit, which is scaled based on the wave height instead of using seasonal normals. More details on the soft time continuity limits are given in Appendix B.

6.2.3.2. TAO

TAO buoys undergo gross time continuity checks for sea surface and subsurface temperatures, as well as rainfall data. If the water temperature at any depth changes by more than 12 °C between consecutive 10-minute observations, the data are flagged and not released. If the level in the rain gauge increases by more than 10 mm between consecutive 1-minute observations, the observation is discarded and not used in the rain rate calculation.

6.2.4. NCEP Model Comparisons

Every six hours, measurements of air temperature, air pressure, and wind speed and direction from Coastal Weather Buoys and C-MAN stations are compared against numerical output from the NCEP Global Forecast System (GFS) model to determine if sensor performance has degraded. The model data are retrieved from the 6-hour forecasts from each of the four daily model runs and interpolated from a 1-degree global grid to the NDBC station locations. If the difference between the 6-hour GFS forecast and the NDBC observation exceeds predefined limits, the measurement is assigned an **n** flag, but it is still released in real-time. The algorithms used to compute the predefined limits are contained in Appendix B.

6.2.5. Duplicate Sensor Checks

Several meteorological measurements on Coastal Weather Buoys and C-MAN stations have duplicate sensors on the same station, so that if one sensor fails the other can be released without loss of data. If both sensors are working, two checks are performed to ensure that they both track together. The first of these checks is a difference check, which assigns a **k** flag if the difference between the two sensors exceeds a predefined threshold. The second check is a tendency check, which assigns a **t** flag if the difference between the hourly rates of change reported by the two sensors exceeds a given threshold. The default tolerance limits for these checks are given in Table 8, although the defaults can be adjusted by NDBC analysts to account for regional and seasonal variations.

Table 8. General Values of Duplicate Sensor Check Thresholds

Variable	**Default Difference Limit**	**Default Tendency Limit (Rate of change per hour)**
Sea-Level Pressure (hPa)	1.0	0.5
Air Temperature (°C)	1.0	0.5
Wind Direction (°)	30.0	20.0
Wind Speed (m/s)	2.0	0.7
Wind Gust (m/s)	4.0	2.5

6.2.6. Related Measurement Check

A related measurement is defined as any measurement that is dependent upon another measurement. For example, the compass heading is related to the wind direction observations, since the compass heading is needed to calculate the wind direction relative to true north. Similarly, air temperature is a related measurement for both dew point temperature and relative humidity. A related measurement is flagged and not released if one or more of the measurements it depends on is hard-flagged. On Coastal Weather Buoys and C-MAN stations, an **R** flag is used to indicate that a related measurement has failed.

6.2.7. Battery Voltage Check

This quality control check is only applicable to Coastal Weather Buoys and C-MAN stations with Legacy payloads. The air pressure sensors on these stations require an input voltage of approximately 12 V, and they can report incorrect values in the event that the input voltage is too low. As a precautionary measure, the air pressure measurements are automatically assigned an **R** flag and not released if the battery voltage drops below 10.5 V.

SCOOP payloads have internal coding that progressively powers down the sensors when the battery voltage drops too low, to conserve power for essential functions such as GPS positioning. As a result, the shoreside battery voltage check is not applied to SCOOP systems, since the air pressure sensors will be powered down automatically before the battery voltage drops low enough to impact the data quality.

6.2.8. Dew Point - Air Temperature Check

On Coastal Weather Buoys and C-MAN stations, the dew point temperature is checked to ensure that it does not exceed the air temperature. If the dew point does exceed the air temperature, it is set equal to the air temperature, and a **c** flag is assigned to the data to warn that the humidity is supersaturated and that the dew point has been adjusted. Refer to Figures 5, 6, and 7 for how dew point temperature is calculated.

6.2.9. Standard Wind Checks

6.2.9.1. Wind Direction & Buoy Azimuth Check

Coastal Weather Buoys with Legacy payloads are equipped with a wind fin, which is designed to keep the buoy heading aligned with the wind direction. This alignment ensures that the anemometers have unobstructed exposure to the winds, without interference from each other or any of the other sensors. If the difference between the mean buoy heading (as measured by the magnetometer in the wave system) and the wind direction exceeds 35 degrees and the wind speed exceeds 10 m/s, then the wind direction is assigned a **z** flag.

6.2.9.2. Gust Ratio Check

On Coastal Weather Buoys and C-MAN stations, the wind gust is compared against the wind speed. If the wind gust is less than the wind speed, the gust is **L** flagged and not released. If the wind gust is greater than the wind speed, then an additional check is performed to ensure that the gust ratio (defined as wind gust divided by wind speed) is within reasonable limits. If the gust ratio exceeds the allowable limit, a **g** flag is assigned to the gust measurement, but it remains released in real-time. The limits for the gust ratio check vary as a function of wind speed; the full algorithm is explained in Appendix B.

For Legacy payloads with continuous winds, this same check is performed to compare the hourly maximum gust against the hourly average continuous wind speed.

6.2.9.3. Compass Check

On Coastal Weather Buoys and C-MAN stations, the raw compass measurement is checked to ensure that it does not flatline at a constant value. If the raw compass reports the same heading for three consecutive measurements, an **s** flag is assigned to the wind direction.

6.2.10. <u>Continuous Wind Checks</u>

The following checks are performed only on stations with continuous winds (C-MAN stations and Coastal Weather Buoys with Legacy payloads).

6.2.10.1. Standard vs. Continuous Wind Speed check

The standard wind speed measurement is compared against the 10-minute continuous wind speed measurement whose time interval includes the averaging period of the standard wind speed. If the difference between them exceeds 2 m/s (buoys) or 3 m/s (C-MAN) an **i** flag is assigned to the continuous wind measurement. The larger tolerance for C-MAN stations is due to the shorter averaging period for the standard measurement.

6.2.10.2. Continuous Wind Standard Deviation check

The standard deviation of the continuous wind speeds is checked against the hourly average wind speed. This value is used internally only and not made available to the public. The standard deviation of the wind speed is expected to increase as wind speed increases. The maximum allowable standard deviation is defined by the relation $\sigma = 2.0 + 0.142v$, where v is the wind speed and σ is the maximum allowable standard deviation. The minimum allowable standard deviation is defined by the relation $\sigma = 0.07v$ for wind speeds of 8 m/s or less, and $\sigma = -0.57 + 0.142v$ for wind speeds greater than 8 m/s. Standard deviations falling outside of these bounds will be **d** flagged.

6.2.10.3. Continuous Wind Related Measurement Check

If the continuous winds report all zeros, then the observations derived from the continuous winds are considered to be suspect and assigned **r** flags. This check consists of two parts:

- **r** flags are assigned to the hourly maximum wind gust and the standard deviation of continuous winds if all six continuous wind speed observations from the last hour are zero, but the hourly wind speed observation is not zero.
- An **r** flag is assigned to the direction of the hourly maximum wind gust if all six continuous wind direction observations from the last hour and the hourly wind direction observation are equal to zero.

6.2.11. <u>Wave Checks</u>

The checks in this section apply specifically to wave measurements, which are only applicable on Coastal Weather Buoys.

6.2.11.1. Wave Heave Consistency Check

NDBC wave systems report the mean, maximum, and minimum heave statistics, which are checked for consistency. If the mean heave is not greater than the minimum heave and less than the maximum heave, then the wave height will be **S** flagged and the data are not released.

6.2.11.2. Wind-Wave Check

Lang (1987) developed an empirical relationship between the 3-hour average wind speed and the spectral wave energy between 0.20 and 0.27 Hz. Based on this relationship, an algorithm was developed in which the 0.20-0.27 Hz spectral energy is predicted based on wind speed observations from the past three hours. If the observed 0.20-0.27 Hz spectral energy does not agree with this prediction within a tolerance threshold, soft flags are assigned to the wave height. **x** flags are assigned if the wave energy is too low for the given wind speed, and **y** flags are assigned if the wave energy is too high. The formulas to calculate the predicted wave energy and the tolerance threshold are given in the Lang paper, and in Appendix B.

6.2.11.3. Calm Sea Check

In calm seas, the signal-to-noise ratio in the spectral wave data becomes very small, and it becomes likely that calculations of dominant period and mean wave direction will be contaminated by noise. As a result, NDBC assigns **U** flags to dominant period and mean wave direction if the significant wave height is less than 0.25 meters.

6.2.11.4. Spectral Wave Direction Validation

The spectral wave directions are evaluated to ensure that they remain in the 0 - 360° range. If any of the spectral frequency bands reports a mean direction outside of this range, the bulk mean wave direction, wind wave direction, and swell wave direction are **S** flagged and not released.

6.2.11.5. Wave Height - Wave Period Check

Ocean wave dynamics place a physical limit on the significant wave height as a function of average wave period. If the wave height is too high, the wave would break and the energy would quickly dissipate. NDBC has derived an empirical formula for the maximum wave height that can be expected for a given average wave period, using equations described in Appendix B. If the significant wave height exceeds this maximum, **p** flags are assigned to both significant wave height and average wave period.

6.2.11.6. Spectral Wave C_{11} Spike Check

At high frequencies, wave spectral energy density (C_{11}) data are expected to follow the Pierson-Moskowitz (1964) spectrum, in which spectral energy is proportional to the negative fourth power of frequency (f). Similarly, the temporal change in spectral energy should also decay proportionally with f^{-4}. This relationship is used to apply a time continuity check to the spectral wave data. If the rate of change in C_{11} exceeds $0.006 \times f^{-4}$ per hour, the significant wave height is **m** flagged. This check is only applied at frequencies above 0.08 Hz, and is not performed if the interval between the previous and current wave observations exceeds one hour.

6.2.11.7. Wave Direction vs. Wind Direction Check

High-frequency (>0.3 Hz) waves are expected to be dominated by the local wind conditions; therefore, the spectral mean wave direction (α_1) at 0.35 Hz is expected to agree with the wind direction. The mean wave direction is assigned a **w** flag if all of the following conditions are true:

- α_1 at 0.35 Hz differs from the wind direction by more than 25°
- The wind speed exceeds 7 m/s
- The wind direction has has not shifted by more than 30° since the previous observation
- The wave spectral energy density (C_{11}) at 0.35 Hz exceeds 0.003 m^2/Hz

6.2.12. <u>Supplemental Measurement Checks</u>

Coastal Weather Buoys and C-MAN stations that are climatologically in the path of hurricanes or other intense storms have the capability to report supplemental measurements including the minimum 1-minute sea level pressure and the maximum 1-minute wind speed. The following algorithms check these supplemental measurements for consistency.

6.2.12.1. Minimum 1-Minute Pressure Consistency Check

The minimum 1-minute sea level pressure is compared against standard sea level pressure measurement. If the difference between them exceeds 10 hPa, an **h** flag is assigned to the minimum 1-minute sea level pressure. If the station has been placed in storm release, the difference must exceed 50 hPa for the **h** flag to be assigned.

6.2.12.2. Maximum 1-Minute Wind Speed Consistency Check

The maximum 1-minute wind speed is compared against the continuous wind measurements for consistency. If the maximum 1-minute wind speed exceeds the maximum 5-second gust or is less than the highest 10-minute continuous wind speed, an **h** flag is assigned to the maximum

1-minute wind speed.

6.2.13. Rain Spike Check

During processing of TAO rain data, the rainfall accumulations are checked for single-point spikes. A spike is detected if a rapid increase and decrease in water level exceeding 0.3 mm occurs in consecutive 1-minute observations. Any spikes are removed from the accumulation time series before calculating the 10-minute average rain rate.

6.2.14. Repeated Value Check

On TAO buoys, there are occasional transmission errors between the subsurface sensors and the surface buoy. Therefore, a series of checks is performed on the real-time subsurface temperature data to identify and flag data corrupted from transmission errors. In addition to range and time continuity checks covered in Sections 6.2.2 and 6.2.3 above, there are also repeated value checks described below.

The subsurface temperature sensors on the TAO array report temperatures to four decimal places, which is two orders of magnitude greater than the sensor accuracy specification. The last two decimal places are therefore expected to fluctuate due to random noise, even in a steady temperature environment. If two or more consecutive measurements are exactly equal, they will be flagged as questionable. Additionally, if simultaneous measurements from two sensors at adjacent depths are exactly equal, then both measurements will be flagged as bad due to the likelihood of at least one of them being erroneous.

6.3. MANUAL QUALITY CONTROL PROCEDURES

In addition to the automated QC checks that are performed in real-time, NDBC performs manual data QC checks on a daily basis. This section describes the flags that are applied manually by NDBC, as well as methods used to override the flags that are applied in real-time.

6.3.1. Sensor Failures

If an NDBC data analyst determines that a sensor is producing unreliable data, the affected measurements will be manually failed in the NDBC database. This ensures that the data from the failed sensor are automatically flagged and not released in real-time. For Coastal Weather Buoys and C-MAN stations, a **D** flag is used to indicate that a measurement was failed manually. For TAO, quality flag **4** is used for any measurement that was manually failed.

6.3.2. Manual Flagging

If an observation was released in real-time, but NDBC later determines that it was suspect, the observation can be manually flagged. This will ensure that the suspect data are flagged in historical archives. For Coastal Weather Buoys and C-MAN stations, an asterisk (*****) flag indicates that an observation was released in real-time, but was later failed by NDBC. For TAO, the numerical quality flags are used.

Similarly, NDBC has the ability to remove flags that were assigned in real-time, if the flagged data are deemed acceptable.

6.3.3. Storm Release

In cases of extreme weather resulting from tropical cyclones or other large-scale intense storms, NDBC has the ability to manually place Coastal Weather Buoys and C-MAN stations in storm release. When a station is in storm release, hard flags assigned during the automated quality control process will not stop the release of the data in real-time. This is done to ensure that critical data will be released during high-impact weather events, in which conditions are likely to exceed the hard limits imposed by the automatic quality control process.

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APPENDIX A: SHORESIDE CONVERSIONS AND DERIVATIONS

This appendix provides the conversion formulas that are used in NDBC shoreside processing to calculate derived measurements.

A1. RELATIVE HUMIDITY / DEW POINT CONVERSIONS

Most Coastal Weather Buoys and C-MAN stations report air temperature and relative humidity, from which dew point temperature is calculated using the following series of equations. First, the saturation vapor pressure (e_s) is calculated from air temperature measured inside the humidity probe (T), by using

$$e_s = exp\left(-\frac{5438}{T+273.15} + 21.72\right)$$

The actual vapor pressure (e) is similarly related to the dew point temperature (T_d):

$$e = exp\left(-\frac{5438}{T_d+273.15} + 21.72\right)$$

By definition, relative humidity (r) is equal to the ratio of vapor pressure to saturation vapor pressure, expressed as a percentage:

$$r = 100\frac{e}{e_s}$$

Therefore, the conversion between relative humidity and dew point temperature can be written as follows:

$$r = \frac{100}{e_s}exp\left(-\frac{5438}{T_d+273.15} + 21.72\right)$$

Or alternatively, in terms of dew point temperature:

$$T_d = -\frac{5438}{ln\left(\frac{e_s r}{100}\right)-21.72} - 273.15$$

MARS payloads do not transmit relative humidity data. Instead, they transmit the calculated dew point temperature, from which the relative humidity is recalculated shoreside using the above equations. One of the weaknesses behind this method is that the air temperature used in the shoreside recalculation is not identical to the temperature measured inside the relative humidity probe. Instead, it is measured by a separate sensor. Modern payloads overcome this weakness by transmitting relative humidity directly.

A2. LONGWAVE RADIATION CALIBRATION

TAO buoys with older payloads (soon to be phased out) report raw measurements of longwave radiation (LWR_{raw}) and case temperature ($T_{C\text{-}raw}$). These raw measurements are used to calculate the thermopile radiation,

$$R_{thermopile-raw} = LWR_{raw} - \sigma(T_{C-raw} + 273.15)^4$$

where σ is the Stefan-Boltzmann constant (5.6697×10^{-8} $W \cdot m^{-2} \cdot K^{-4}$). Newer payloads report the raw sensor voltage outputs for thermopile radiation and case temperature, which are converted to physical units by applying a conversion factor during shoreside processing.

For both types of payloads, linear calibration coefficients are applied to both the thermopile radiation and the case temperature. The resultant values ($R_{thermopile\text{-}adj}$ and $T_{C\text{-}adj}$) are used to calculate the calibrated longwave radiation measurement (LWR_{adj}):

$$LWR_{adj} = R_{thermopile-adj} + \sigma(T_{C-adj} + 273.15)^4$$

A3. BULK WAVE PARAMETERS

A3.1. Significant Wave Height (H_s):

NDBC calculates significant wave height from the wave spectrum using the following equation:

$$H_s = 4 \times \sqrt{\sum_f C_{11}(f) \times d(f)}$$

where:

- $C_{11}(f)$ = Variance spectral energy (m^2/Hz) at each frequency bin
- f = Frequency (Hz)
- d(f) = Width of each frequency bin (Hz)

A3.2. Dominant Wave Period (T_p):

Dominant period is equal the inverse of the frequency of the spectral peak:

$$T_p = 1/f_p$$

where f_p is the center of the frequency bin containing the peak spectral energy (C_{11})

A3.3. Average Wave Period (T_m)

Average wave period is calculated from the second frequency moment of the wave spectrum. It approximates the mean period that would be obtained from a zero-crossing analysis of the wave elevation record. The equation for average wave period is as follows:

$$T_m = \sqrt{\frac{\sum_f \left(C_{11}(f) \times d(f)\right)}{\sum_f \left(C_{11}(f) \times d(f) \times f^2\right)}}$$

where:

- $C_{11}(f)$ = Variance spectral energy (m^2/Hz) at each frequency bin
- f = Frequency (Hz)
- d(f) = Width of each frequency bin (Hz)

A4. WIND-SWELL SEPARATION FREQUENCY

The wind-swell separation frequency is calculated by defining a wave steepness parameter (ξ) as a function of frequency:

$$\xi(f) = \frac{8\pi m_2(f)}{g\sqrt{m_0(f)}}$$

where

$$m_n = \int_f f^n C_{11}(f) df$$

The separation frequency is estimated by

$$f_s = 0.75 f_x$$

where f_x is the frequency at which the steepness parameter is maximized. To improve performance in light winds, the separation frequency is constrained as follows:

$$f_s \geq \frac{1.25C}{U_{10}}$$

where C is an empirically determined constant equal to 0.9, and U_{10} is the measured wind speed adjusted to 10 meters.

APPENDIX B: QUALITY CONTROL ALGORITHMS

This appendix is intended to provide details and/or examples of QC algorithms beyond what is covered in the main sections of this document. Algorithms that are too complex to be fully described in the main sections are explained here.

B1. COASTAL WEATHER BUOY AND C-MAN TIME CONTINUITY CHECKS

The standard time continuity check developed at NDBC is based on the following expression:

$$\sigma_T = \sigma\sqrt{2(1 - R(T))}$$

where σ_T is the standard deviation about the mean difference between measurements at a specific time and the corresponding measurements T hours later, x(t+T). σ is an estimate of the standard deviation of an ensemble of measurements, and R(T) is the autocorrelation function of an ensemble of measurements for a time lag, T.

Statistics were gathered for a number of stations ranging from the Gulf of Alaska to the Gulf of Mexico. It was determined that there is an approximate linear relationship between R(T) and T for values of T less than 12 hours. Therefore, σ was recast as follows:

$$\sigma_T = c\sigma\sqrt{T}$$

This is a practical representation of the general change of a normally distributed meteorological or oceanographic variable with time. The mean 1- to 24-hour changes in atmospheric pressure were determined for a number of stations, and it was found that c equal to 0.58 provided a suitable limit for the naturally allowable change in barometric pressure with time, yielding the following:

$$\sigma_T = 0.58\sigma\sqrt{T}$$

The parameter T in the above equation is equal to the number of hours elapsed since the previous valid observation, rounded down to the nearest whole hour. If T is equal to zero, it is adjusted to 0.5, and values of T greater than 3 are adjusted to 3. If the difference between two consecutive measurements exceeds σ_T, the latest measurement is **V**-flagged.

The soft time continuity check works similarly, except that the limits are defined as a maximum absolute ΔX/ΔT, where ΔX is the change in the observed value and ΔT is the number of hours elapsed between the previous and current observations. As before, ΔT is rounded down to the nearest whole hour and then constrained between 0.5 and 3 hours. If ΔX/ΔT exceeds the limit, the latest observation receives an **f** flag.

Special rules are put in place for significant wave height observations, which scale the soft time continuity limit based on the previous wave height observation. For significant wave height, the maximum allowable absolute ΔX (ΔX_{max}) is calculated given the previous wave height observation (WH_{prev}) and ΔT:

- If ΔT < 1 hour, the standard soft continuity algorithm is used.
- If ΔT = 1 hour, $\Delta X_{max} = (WH_{prev} + 0.9) / 3.92$
- If ΔT = 2 hours, $\Delta X_{max} = 1.41 \times (WH_{prev} + 0.9) / 3.92$
- If ΔT > 2 hours, the time continuity check is not performed.

As before, observations that fail the check are assigned an **f** flag.

B2. NCEP MODEL COMPARISONS

Comparing NDBC measurements with NCEP fields interpolated to station location is a powerful way to identify sensor degradation. Though the checks are essentially range checks, some of the checks have range limits that vary in a simple manner with geography and values of other measurements.

For each check, the NCEP-produced 6-hour forecast field, valid at 00Z, 06Z, 12Z, and 18Z is interpolated to the station location, and the absolute value of the difference between the model-interpolated value and the station measurement is calculated. If the limit is exceeded for any measurement, an **n** flag is assigned.

B2.1. Sea Level Pressure

Model performance is best in areas where the pressure gradient is small. Pressure variation is lowest at low latitudes, and in areas of high pressure. Therefore, the maximum allowable difference between the model-interpolated and observed pressures varies depending on latitude and the observed pressure:

Latitude	Observed Pressure	Maximum Absolute Difference
< 30°	Any	2.5 hPa
≥ 30°	> 1008 hPa	2.5 hPa
	995 - 1008 hPa	4.0 hPa
	≤ 995 hPa	6.0 hPa

B2.2. Air Temperature

Model performance is sometimes poor near the U.S. West Coast due to the tight temperature gradients that develop between the Pacific Ocean and the nearby land areas. Stations between 110° and 129° west longitude allow the observed temperature to be up to 10°C colder or 5°C warmer than the model-interpolated temperature. For other stations, the difference limit is ± 3°C.

B2.3. Wind Direction

The wind direction check is variable depending on the wind speed. For the purpose of the wind direction check, the wind speed is set equal to the lower of the model-interpolated wind speed and the observed wind speed adjusted to 10 m height. The tolerance limit is then calculated as follows:

Wind Speed	Wind Direction Tolerance Limit (°)
≤ 5 m/s	Check is not performed
5 - 10 m/s	(15.6 - Wind Speed) / 0.188
> 10 m/s	30

B2.4. Wind Speed

Like the wind direction check, the wind speed check is variable depending on the wind speed. The tolerance is defined using the algorithm described below. For the purpose of this algorithm, let MDL equal the model-interpreted wind speed, OBS equal the observed wind speed adjusted to 10 m height, and the quantity A equal to the lower of MDL and OBS.

- If A > 12.35 m/s, tolerance = 2.25 m/s
- If 12.35 m/s > A ≥ 6 m/s, tolerance = (16.6 - A) / 1.67 m/s
- If OBS < 6 m/s, tolerance = 5 m/s.
- If none of the above conditions are met, the check is not performed.

B3. GUST-TO-SPEED RATIO CHECK

The gust ratio (GR) is defined as the gust (GUST) divided by the wind speed (WSPD):

$$GR = \frac{GUST}{WSPD}$$

The maximum allowable gust ratio (GR_{max}) is defined as follows:

$$GR_{max} = 1 + \frac{1}{1.98 - (1.887 \times exp(-0.18 \times GUST))} + C$$

The parameter, C, is a piecewise function of wind speed:

Wind Speed (m/s)	C
< 0.3	5.0
0.3 - 1.0	3.0
1.0 - 3.0	0.7
3.0 - 6.0	0.35
≥ 6.0	0.2

A **g** flag is assigned if GR > GR_{max}. If the wind speed exceeds the wind gust (GR < 1), then the wind gust is hard-flagged and not released. This same check is used on stations with continuous winds to compare the hourly maximum gust to the hourly average wind speed.

B4. WIND-WAVE ALGORITHM

The wind-wave algorithm, developed by Lang (1987), is based on an empirical relationship between the observed wind speed averaged over the last three hours and the spectral wave energy at frequencies between 0.20 and 0.27 Hz.

First, calculate the 3-hour average wind speed (m/s), adjusted to a 5-meter height (W3), then take the square of the result (W3SQ). The predicted wave energy between 0.20 and 0.27 Hz and the upper limit are defined as piecewise functions of W3SQ:

W3SQ (m^2/s^2)	Wave Energy Prediction	Wave Energy Upper Limit
16 or less	Check is not performed (wind speed too low)	
16 to 88	0.067 * W3SQ + 0.1	0.08 * W3SQ + 2.8
88 to 230	0.0335 * W3SQ + 3.4	0.0356 * W3SQ + 6.7
Greater than 230	0.0087 * W3SQ + 9.2	0.0087 * W3SQ + 13.0

The lower limit of the 0.20-0.27 Hz spectral wave energy is equal to twice the predicted value minus the upper limit.

If the spectral energy is less than the lower limit, the wave height is assigned an **x**-flag.
If the spectral energy is greater than the upper limit, the wave height is assigned a **y**-flag, unless all of the following conditions are met:

- The 3-hour average wind speed is steadily decreasing over the past two hours, or the tendency of the 3-hour average wind speed has changed signs in the last two hours.
- No y-flags have been assigned in the last two hours.
- The 0.20-0.27 Hz spectral wave energy is less than predicted value plus twice the difference between the upper limit and the predicted value.

B5. WAVE HEIGHT - WAVE PERIOD CHECK

NDBC empirically defines the maximum allowable significant wave height (H_{Smax}) as a piecewise function of the average wave period (T_{avg}):

$$T_{avg} \leq 5s: H_{Smax} = 1.16 \times T_{avg} - 2$$

$$T_{avg} > 5s: H_{Smax} = 0.25 \times T_{avg} + 2.55$$

If the significant wave height exceeds H_{Smax}, both the significant wave height and the average wave period are **p**-flagged.

APPENDIX C: QUALITY CONTROL FLAGS

HARD FLAGS

Flag	Description	Section in Document
D	Sensor failed by analyst	6.3.1
L	Failed range limit check	6.2.2; 6.2.9.2
M	Missing sensor data	N/A
R	Failed related measurement check or battery voltage check	6.2.6; 6.2.7
S	Invalid statistical parameter in wave data	6.2.11.1; 6.2.11.4
T	Transmission parity error	6.2.1
U	Insufficient wave energy to calculate dominant period	6.2.11.3
V	Failed time continuity check	6.2.3
W	Wave data processing error	6.2.1
*	Measurement manually flagged	6.3.2

SOFT FLAGS

Flag	Description	Section in Document
a	Measurement is above the upper monthly, regional limit	6.2.2
b	Measurement is below the lower monthly, regional limit	6.2.2
c	Dew point adjusted to not exceed air temperature	6.2.8
d	Failed continuous wind standard deviation check	6.2.10.2
f	Failed soft time continuity check	6.2.3
g	Failed gust ratio check	6.2.9.2
h	Failed supplemental measurement check	6.2.12
i	Continuous and standard wind speeds do not agree	6.2.10.1
j	A single parity error exists in the continuous winds	6.2.1
k	Difference between duplicate measurements is too high	6.2.5
m	High-frequency spikes detected in the wave spectrum (C_{11})	6.2.11.6
n	Measurement does not agree with NCEP model output	6.2.4
p	Failed wave height and period comparison check	6.2.11.5
r	Related measurement failed (continuous winds only)	6.2.10.3
s	Failed stuck compass check	6.2.9.3
t	Tendency difference between duplicate sensors is too high	6.2.5
v	Failed relative humidity versus visibility check	N/A
w	Failed wave direction vs. wind direction check	6.2.11.7
x	Wind wave energy is too low for prevailing wind speed	6.2.11.2
y	Wind wave energy is too high for prevailing wind speed	6.2.11.2
z	Failed bow azimuth versus wind direction check.	6.2.9.1