

The Earthscope US transportable array 1 Hz surface pressure dataset

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A unique set of high temporal frequency surface atmospheric pressure observations have been collected and archived from a large-scale field campaign in the geosciences. The Earthscope U.S. Transportable Array (USArray TA) consists of approximately 400 deployable surface platforms. Stations were deployed in a Cartesian-like gridded fashion across a section of the contiguous United States for 1–2 year then retrieved and redeployed as new platforms further east. While primarily deployed for seismic measurements, platforms also recorded surface atmospheric pressure. These pressure data, collected and stored at a temporal frequency of 1 Hz, have been made available via the Research Data Archive at the National Center for Atmospheric Research (NCAR) for the time period 1 Jan 2010–31 Dec 2015. The 6 years of observations contain data from over 1000 locations ranging from the central to eastern United States, as well as some platforms in Alaska and the northwest United States. Data were organized as annual station files with supplemental metadata and quality control summary files. Several web-based interfaces are also available to rapidly explore the pressure archive. We describe the available dataset with several prominent atmospheric events shown as usage examples.

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Introduction

Observations of atmospheric pressure remain an important source of information for many disciplines within the field of meteorology. These observations have been a critical piece for identification of weather phenomena at multiple physical scales, as well as understanding common propagation characteristics (e.g., Zishka and Smith, 1980; Chenoweth, 2014; Rupert and Bosart, 2014). With improved computational power, surface, and derived sea-level pressure data have been compared and incorporated into numerical

analyses and reanalyses to improve accuracy and depiction of atmospheric events (Whitaker *et al.*, 2004; Compo *et al.*, 2006, 2011). Recent advances in numerical data assimilation techniques have also relied on surface and derived pressure quantities (e.g., pressure tendency) with efforts to improve simulations of mesoscale phenomena (Anderson *et al.*, 2005; Ingleby, 2014; Lei and Anderson, 2014; Madaus *et al.*, 2014). Further, measurements of surface pressure lack the common representativeness errors that can affect other atmospheric state variables (e.g., temperature), beyond requiring an accurate elevation above sea level

for the site. This broadens the potential to use pressure observations recorded from a wide variety of sources ranging from fixed *in situ* weather stations to mobile phones (Mass and Madaus, 2014).

An extensive National Science Foundation (NSF) geoscience field campaign, known as The Earthscope Initiative, has been conducted over the past decade to better understand and map the structural detail underneath the North American continent. One phase of this campaign, called the US Transportable Array Network (USArray TA), involved the temporary deployment of surface platforms in a pseudo-grid formation to provide enhanced information on seismic activity as well as geospatial mapping of the continent itself (Tytell *et al.*, 2016). Seismic observations are known to be affected by atmospheric 'signals' including bolide events (Hedlin *et al.*, 2010) and human-caused acoustic signals (de Groot-Hedlin *et al.*, 2008; Hedlin *et al.*, 2012) as well as pressure perturbations from natural atmospheric phenomena such as gravity waves (de Groot-Hedlin *et al.*, 2014). As more resources became available to do so, atmospheric pressure sensors recording at high temporal resolution (1 and 40 Hz) were added to the TA platforms to help identify these non-seismic perturbations encountered in the seismic data (Tytell *et al.*, 2016).

Surface atmospheric pressure data at such high temporal resolution over an extensive area has not been available before, making these data a unique resource for atmospheric research. Jacques *et al.* (2015) and Tytell *et al.* (2016) illustrate a number of atmospheric applications derived from subsets of the USArray TA pressure dataset. We summarize here, for the USArray TA pressure sensor period of record through 2015, the platform and sensor deployment strategy, sensor metadata and quality control, data format, availability, and additional examples of its use for meteorological applications. Further, we describe an archive of the pressure dataset derived from the 1 Hz observations from 1 Jan 2010 – 31 Dec 2015 that is now publicly accessible from the Research Data Archive (RDA) at the National Center for Atmospheric Research (NCAR). This permanent archive will be updated on an annual basis throughout the remaining lifetime of the TA program.

1. Dataset description and collection

1.1. USArray TA platforms

The TA deployment methodology consisted of approximately 400–500 platforms, which were placed using a Cartesian-like strategy across a subsection of the contiguous United States (CONUS). Each platform was spaced ~70 km apart from the adjacent sites, forming an array-like appearance when considering all deployments spatially. A single platform recorded and transmitted data in real time for a period of about 1–2 years before being retrieved. After retrieval, a platform would be maintained and repaired, if necessary,

and redeployed to a new site along the eastern edge of the TA footprint. From its initial deployment in 2004 through the end of the main CONUS deployment phase in 2015, the TA appeared to 'move' east with time.

Since ~500 pressure sensors began to be added roughly halfway through the project, Figure 1 depicts the ~1000 locations for which pressure observations are available primarily from the central CONUS eastward during the 2010–2015 period. A separate array of platforms is in place near the Cascade Mountain Range in the northwest CONUS, while some additional TA stations were adopted by other organizations and remain in place as part of the Central and Eastern United States Network initiative (Tytell *et al.*, 2016). The primary portion of the TA is now transitioning from the CONUS to deployment in Alaska and adjacent Canadian provinces with a similar gridded array of platforms to evolve there over the next several years.

Tytell *et al.* (2016) describe a typical TA platform deployment, which consists of a below-surface vault enclosing the seismometer and additional equipment. The atmospheric pressure sensor is placed adjacent to the primary data logger near the top of the vault with tubing extending upwards to allow adequate sensor exposure. Most platforms rely on solar power and batteries to power the sensor, logging, and communication systems, which allow CONUS stations to transmit data in real-time with minimal latency.

Three types of pressure sensors were typically installed on each platform: infrasound microphones for very high frequency (0.1–100 Hz) pressure perturbations as well as Micro-Electro-Mechanical (MEMS) and Setra-278 pressure sensors. As described by Jacques *et al.* (2015), the more expensive Setra-278 is the preferred sensor for our uses due to its superior performance characteristics. The Setra-278 sensors provide an accuracy of 0.5–1.0 hPa, resolution of 0.01 hPa, and long-term stability of 0.1 hPa year⁻¹. The MEMS sensors provide similar metrics of 1.5 hPa accuracy, 0.015 hPa resolution, and 1.0 hPa year⁻¹ stability (Jacques *et al.*, 2015). The combination of good accuracy and stability of the Setra-278 sensor with the relatively short lifetime of equipment deployment per site provide added confidence in data quality. Sensors were recalibrated or replaced as necessary, typically when a platform was retrieved from its previous location to eventually be redeployed. Data from MEMS sensors are used to fill in any small gaps and complete the data archives when Setra-278 data are unavailable.

Seismic and pressure data are collected in real time and stored in repositories hosted by the Incorporated Research Institutions for Seismology (IRIS) Data Management Center (Tytell *et al.*, 2016). For the data archive described here, 1 Hz surface pressure observations have been collected daily from IRIS and stored at the University of Utah after initially backfilling to begin the archive on 1 Jan 2010. Data are requested from IRIS after a 2-day delay to minimize data loss

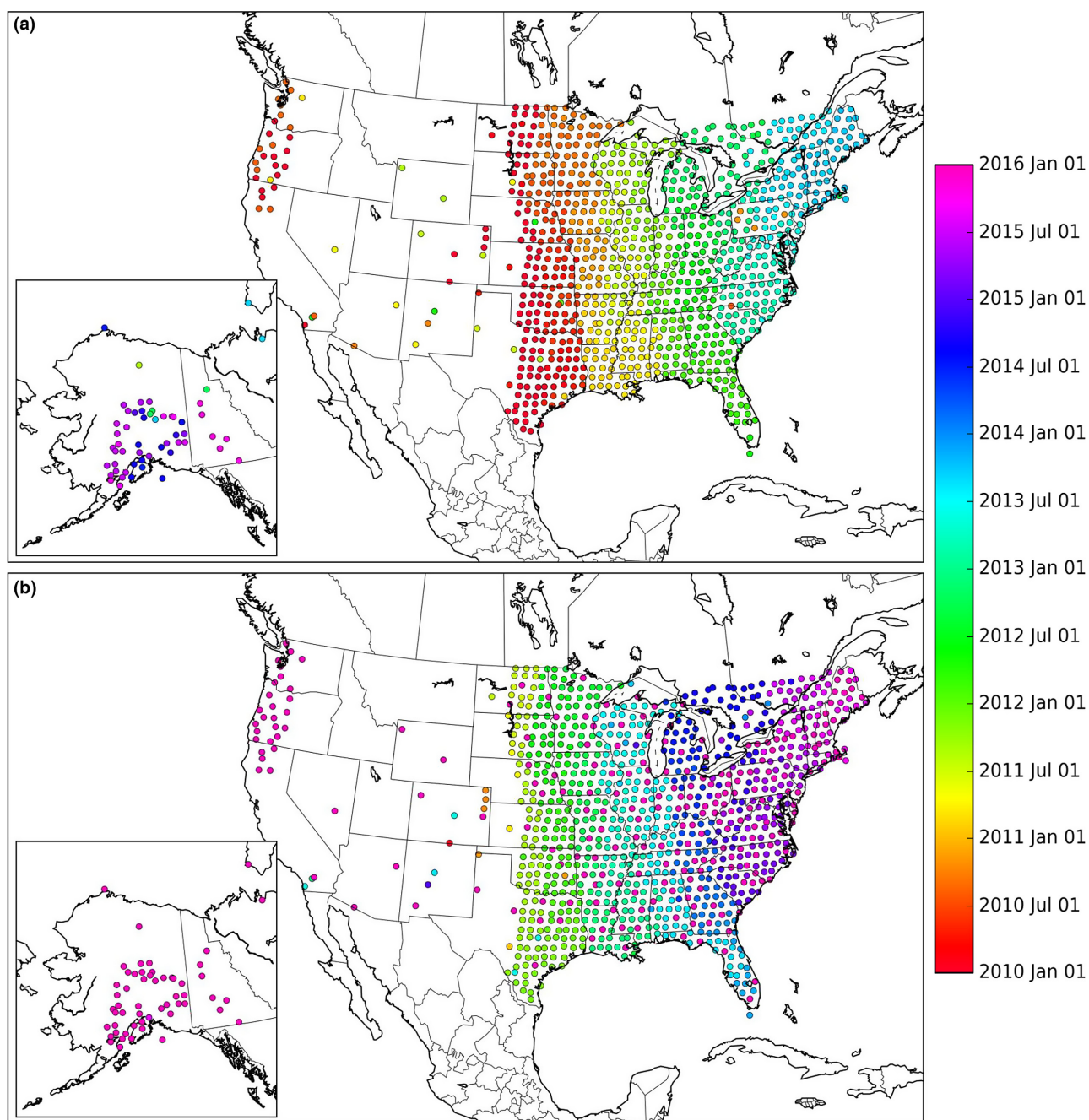


Figure 1. USArray TA station deployments from 1 Jan 2010 through 31 Dec 2015. Marker colour indicates when the station (a) first transmitted data and (b) last transmitted data. Magenta colours indicate stations likely still deployed and transmitting beyond 31 Dec 2015.

arising from real-time communication or data transfer issues between the platforms and IRIS.

1.2. Data quality control and platform uptime

As described by Tytell *et al.* (2016), analysts at Scripps Institution of Oceanography review and quality control all data collected from the TA platforms with weekly quality control reports available to researchers. An additional objective pressure rate-of-change check

of 2 hPa s^{-1} has been applied as well as subjective reviews of the platform time series for spurious observations, in particular those with a rate-of-change greater than 2 hPa min^{-1} (Jacques *et al.*, 2015). Subjective reviews of altimeter-corrected pressure observations were also executed to assist in confirmation that the platform's listed elevation above sea level was correct. Observation time periods that either fail the objective rate-of-change check or the subjective checks indicated above are then flagged as suspect. Time ranges within which platform observations may

be suspect are recorded within the quality control summary dataset.

Over 68 billion surface pressure observations were collected from 1064 locations during the period 1 Jan 2010–31 Dec 2015 (Table 1). The typical (median) station recorded 99.79% of its possible pressure values with a small loss (order 0.1%) arising from the quality control procedures in place. Hence, high quality pressure observations are available nearly continuously from an overwhelming majority of the platforms. At any one time, a very small number of platforms may be experiencing sensor problems (e.g., plugged inlet tubing) or loss of power.

2. RDA data archive

Hierarchical Data Format Version 5 (HDF5) was selected in order to handle the high temporal frequency and volume of this dataset. This open and extensible format, designed for use with large and complex scientific datasets, not only can minimize storage space but also maximize access speed. Approximately, two yearly HDF5 files per station have been created since platforms were typically deployed at each location for 2 years (Table 1). The Python scripting language and PyTables hierarchical data format module were used to create the HDF5 repository from the data obtained from IRIS.

Data are stored using a table-based concept for a defined node within the HDF5 file. Observational tables contain rows for each observation, with columns denoting the valid observation timestamp (integer epoch seconds) and surface pressure (hPa). Each data file also contains descriptors for each table column and platform metadata, including a numeric station identifier, station character identifier (e.g., H62A), latitude, longitude, and elevation above sea level. Finally, a sortable index is associated with the timestamp column to decrease the time required to read data over a time range.

Table 1. USArray TA metrics derived from the dataset archived within the NCAR RDA.

Description	Quantity
Total Platforms	1064
Total Annual Data Files	3075
Total 1 Hz Observations	68 537 083 579
Total HDF5 Repository Disk Space	~85 Gb
Median Station Reporting Period	662.6 days
Median Station Observations Reported	57 253 228
Median Station Uptime (recorded/expected observations)	99.79%
Median Station Data - Passed Quality Control (good/expected)	99.68%

Metrics are valid for data available from 1 Jan 2010 to 31 Dec 2015.

Level 7 Z-Lib compression was applied to each HDF5 file to reduce disk space, yet allow for fast querying without the need to uncompress the entire file. A complete annual station file, which may contain over 30 million observations requires only 40 Mb. For the 3075 annual data HDF5 files, only 85 Gb of disk space are required (Table 1).

Metadata and quality control summary files corresponding to each annual data file also rely on HDF5. Records in the metadata, quality control, and data files are related to one another through the numeric and character station identifiers. The metadata summary files contain geolocation and period of record information for each platform. Annual quality control summaries for each platform contain those temporal ranges within which observational data may be suspect as a function of the quality control type. Although at this time there is only one set of tests (see Section 1.2), future annual data files may be subject to additional tests applied to the data beyond 31 Dec 2015.

The archive of these pressure data maintained at the University of Utah has also been placed in the RDA repository and made accessible to the public utilizing RDA resources (<http://rda.ucar.edu/datasets/ds386.0/>). This archive contains all TA pressure observations, platform metadata, and quality control summaries from 1 Jan 2010 to 31 Dec 2015. Registered users of the RDA can utilize web-based interfaces to explore the available archive geographically and temporally. Further, a dataset citation service is also provided by the RDA which allows users to build proper dataset citations when downloading and accessing data from the archive. Annual updates for the RDA archived dataset with new data, metadata, and quality control summaries beyond 31 Dec 2015 are planned as the TA continues to transition into Alaska.

3. Utilizing the pressure archive

As part of the research described by Jacques *et al.* (2015), a website has been developed and maintained to visualize the TA pressure data in addition to other atmospheric data. These resources are particularly useful to discover locations and periods when atmospheric pressure perturbations may be of interest to a user before downloading data from the archive available from the RDA. The website (<http://meso1.chpc.utah.edu/usarray>) provides time series and maps of surface pressure and a number of derived quantities obtained from the surface pressure data (e.g., altimeter pressure and pressure perturbations within specific temporal bands).

These web interfaces access the archive at the University of Utah as well as a more restricted amount of real-time 1 Hz TA pressure data available from IRIS. Observations can be plotted with respect to surface wind observations courtesy of MesoWest (Horel *et al.*, 2002) as well as the Iowa Environmental Mesonet Web Map Service (WMS) national composite

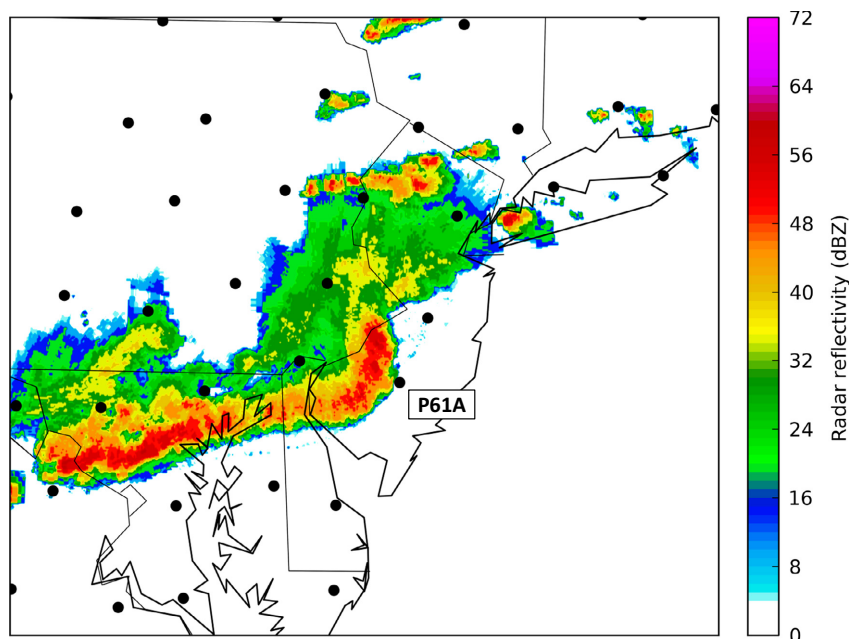


Figure 2. Base radar reflectivity centred on New Jersey at 2220 UTC 23 Jun 2015. Active TA stations are shown as black markers with station P61A (Hammonton, NJ) labelled for reference to Figure 2. Reflectivity imagery courtesy the Iowa Environmental Mesonet web services.

radar reflectivity imagery. Efficient querying within the HDF5 files has made it possible to interactively plot, for example, time series of lengths up to 45 days

within the time of a typical web browser loading sequence. By default, the web tools mask observations deemed suspect by the quality control

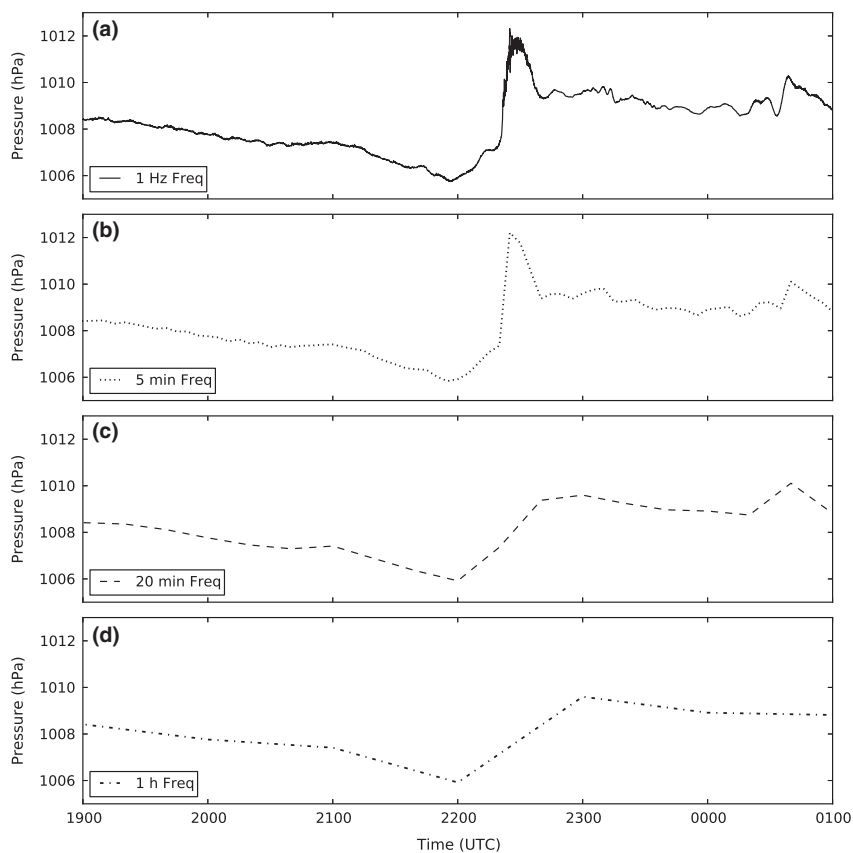


Figure 3. Pressure time series data recorded by TA station P61A (Hammonton, NJ) from 1900 UTC 23 Jun to 0100 UTC 24 Jun 2015. Data shown at sampling frequencies of (a) 1 Hz, (b) 5 min, (c) 20 min, and (d) hourly.

procedures, although the masking can be deactivated to view the raw data.

Many users may not require the high temporal frequency of the pressure data available from the RDA and, hence, would prefer not to have to download all the data in order to process them into time-averaged values. TA pressure observations have already been processed in real-time into 5-min average values and archived in databases as part of MesoWest at the University of Utah (Horel *et al.*, 2002). The observations are available and can be accessed with other meteorological surface observations collected by MesoWest through interactive web tools (<http://mesowest.utah.edu>) and API services (<http://synopticlabs.org/api>). Those 5-min averages have also been

disseminated in near-real time routinely to the National Weather Service via the Meteorological Automated Data Ingest System and thereby distributed further to the National Centers for Environmental Prediction for use in operational numerical weather prediction and other applications.

4. Visualizing the pressure archive resources

As shown by Jacques *et al.* (2015) and Tytell *et al.* (2016), the TA data archive is a very useful resource for examining pressure signatures from mesoscale events for which conventional pressure observations may lack sufficient temporal resolution to resolve

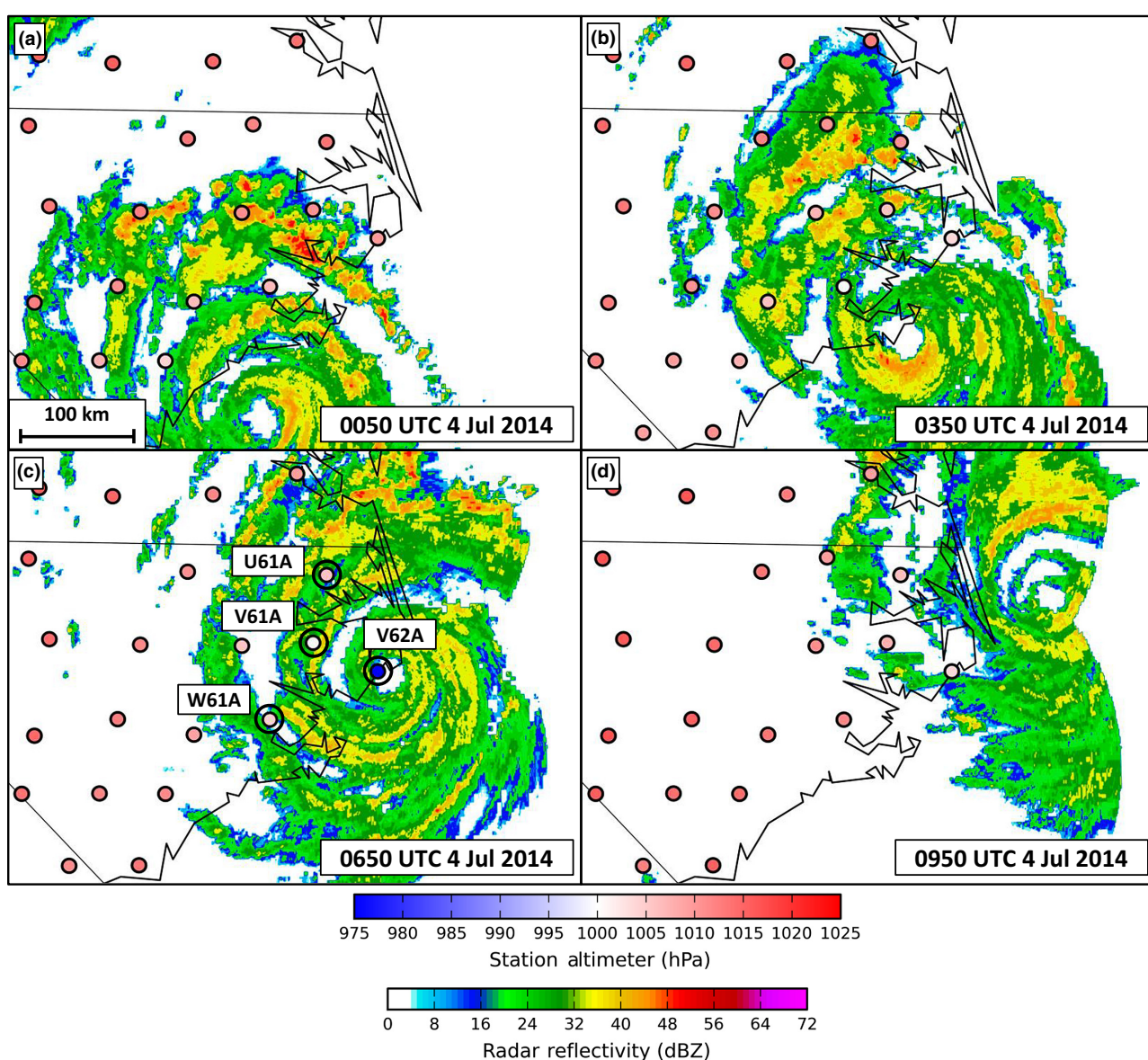


Figure 4. Transect of Hurricane Arthur across coastal North Carolina at (a) 0050, (b) 0350, (c) 0650, and (d) 0950 UTC 4 July 2014. TA altimeter-corrected pressure observations are shown as colored markers with blue (red) indicating lower (higher) pressure, with relevant stations shown in Figure 5 circled and labeled in (c). Radar reflectivity imagery also displayed courtesy of the Iowa Environmental Mesonet Web Map Services.

them. For example, consider the well-defined mesoscale convective system in Figure 2 with a prominent bowing feature evident from radar reflectivity at 2220 UTC 23 Jun 2015 approaching TA station P61A (Hamonton, NJ) at that time. The time series of surface pressure available from that station (Figure 3(a)) has a well-defined sharp pressure rise associated with the passage of the mesoscale convective system. However, the transect time and magnitude of the pressure rise becomes distorted when observations are sampled at intervals longer than 5 min (Figures 3(c,d)), which are still commonplace with many real-time conventional observation networks.

TA surface pressure can also be used effectively to assess larger-scale meteorological phenomena as well, as shown in Figure 4. The TA platforms were deployed near the eastern coast of North Carolina during 4 July 2014 at the time of the landfall of Hurricane Arthur. Arthur reached the North Carolina coastline as a Category 2 hurricane with a minimum central pressure of 973 hPa (Berg, 2015). As the hurricane strengthened and made landfall shortly after 0300 UTC 4 July 2014, its centre passed directly over TA station V62A (Hyde County Airport, NC) between 0630 to 0700 UTC. Figure 5 depicts altimeter-corrected pressure time series for V62A and the three adjacent TA sites U61A (Possum Corner Farms, NC), V61A (Roper, NC), and W61A (Ground Anchor Farm, NC), located directly to its west. Strong pressure gradients can be seen both spatially (Figure 4(c)) and temporally (Figure 5), with a minimum altimeter setting of 975.2 hPa occurring around 0650 UTC 4 July 2014 at V62A, slightly higher than the minimum central pressure recorded from the storm at peak intensity. Altimeter-corrected observations at that time from the surrounding stations were calculated to be 1006.1, 1000.0, and 1004.6 hPa, respectively. Jacques *et al.* (2015) provides an additional large-scale example of TA data use for a rapidly strengthening northeastern CONUS snowstorm on 13–15 February 2014. These examples demonstrate that the TA can be a potentially valuable additional

resource to conventional observations for assessing both the spatial scale and spatial gradients of larger-scale atmospheric phenomena.

5. Summary

Surface pressure observations originating from a long-term geoscience field campaign have been collected and made available in a variety of forms for atmospheric scientists. Observations at 1 Hz temporal frequency were collected from over 1000 different platforms deployed at various periods from 1 Jan 2010 to 31 Dec 2015 as part of the USArray TA initiative. At any given time 400–500 platforms were deployed in a Cartesian-grid configuration. The retrieval and redeployment of platforms along the eastern edge of the primary array resulted in stations being located across the CONUS Central Plains (2010–2011), Ohio Valley to the Gulf Coast (2012–2013), and finally along the East Coast (2014–2015). Each platform recorded approximately 1–2 year of pressure observations with high reliability and data quality (Table 1).

A complete archive of these data, metadata, and quality control summaries have been made available via the RDA. Data are organized into annual station time series files, using HDF5 for data compression and fast time series querying. In order to obtain quick looks at the information available in the RDA, the 1 Hz data are also accessible graphically as time series and maps (<http://meso1.chpc.utah.edu/usarray>) as well as 5-min averages in the MesoWest web (<http://mesowest.utah.edu>) and API services (<http://synopticclabs.org/api>).

A new phase of the TA is now underway in Alaska, with many platforms now providing data (Figure 1). Final deployments in Alaska are expected in 2017 as a similar gridded array is completed there. We intend to continue collecting the 1 Hz pressure data courtesy of IRIS as long as pressure observations are available. These data will continue to be appended to the 1 Hz

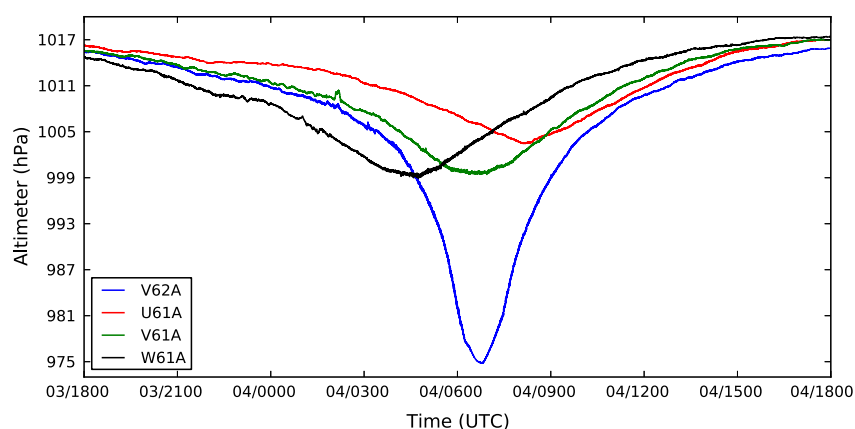


Figure 5. Altimeter-corrected time series plots of TA data from stations V62A (Hyde County Airport, NC - blue), U61A (Possum Corner Farms, NC - red), V61A (Roper, NC - green), and W61A (Ground Anchor Farm, NC - black) during the transect of Hurricane Arthur (1800 UTC 3 July - 1800 UTC 4 July 2014). See Figure 4 for TA spatial location reference.

archives at the University of Utah as well as made available as 5-min averages via MesoWest. The RDA archive is planned to be updated annually with new observations, metadata, and quality control metrics.

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