Ship- and island-based soundings from the 2016 El Niño Rapid Response (ENRR) field campaign

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Abstract. As the 2015/2016 El Niño was gathering strength in late 2015, scientists at the Earth System Research Laboratory's Physical Sciences Division proposed and led the implementation of NOAA's El Niño Rapid Response (ENRR) Field Campaign. ENRR observations included wind and thermodynamic profiles of the atmosphere over the near-equatorial east-central Pacific Ocean, many of which were collected from two field sites and transmitted in near-real time for inclusion in global forecasting models. From 26 January to 28 March 2016, twice-daily rawinsonde observations were made from Kiritimati (pronounced "Christmas") Island (2.0°N, 157.4°E; call sign CXENRR). From 16 February to 16 March 2016, three to eight radiosondes were launched each day from the NOAA Ship *Ronald H. Brown* (allocated call sign WTEC) as it travelled southeast from Hawaii to service Tropical Atmosphere Ocean (TAO) buoys along longitudes 140°W and 125°W and then north to San Diego, California. Both the rapid and the remote nature of these deployments created particular difficulties in collecting and disseminating the soundings; these are described together with the methods used to reprocess the data after the field campaign finished. The reprocessed and lightly quality-controlled data have been put into an easy-to-read text format, qualifying them to be termed "Level 2" soundings. They are archived and freely available for public access at NOAA's National Centers for Environmental Information (NCEI) in the form of two separate data sets: one consisting of 125 soundings from Kiritimati Island (~~doi:~~https://doi.org/10.7289/V55Q4T5K), the other of 193 soundings from the NOAA Ship *Ronald H. Brown* (~~doi:~~https://doi.org/10.7289/V5X63K15). Of the Kiritimati soundings, 94% reached the tropopause and 88% reached 40 hPa, while 89% of the ship's soundings reached the tropopause and 87% reached 40 hPa. The soundings captured the repeated advance and retreat of the ITCZ at Kiritimati, a variety of marine tropospheric environments encountered by the ship, and lower-stratospheric features of the 2015-2016 QBO (quasi-biennial oscillation), all providing a rich view of the local atmosphere's response to the east-central Pacific's extremely warm waters during the 2015/16 El Niño.

Keywords. El Niño, radiosondes, rawinsondes, wind profiles, thermodynamic soundings, tropical Pacific, central Pacific, tropopause, stratosphere, quasi-biennial oscillation

1 Introduction

In early 2015, signs of a long-anticipated El Niño event began to appear in the Pacific Ocean. Both dynamical and statistical models were forecasting the continuation and likely strengthening of El Niño conditions in June 2015 (Climate Prediction Center (CPC) and International Research Institute for Climate and Society (IRI), 2015a). By August 2015, CPC and IRI (2015b) were describing the event as "significant" with high confidence that a strong event would peak in the late fall or early winter. The National Oceanic and Atmospheric Administration (NOAA), aware of the potential for large impacts to weather in the United States, wanted to respond quickly to the emerging forecasting challenges. Thus, the El Niño Rapid Response (ENRR) program was instituted as a joint effort by both operational and research-oriented sectors within NOAA. Coordinated, targeted field work was proposed as one element of ENRR by the Earth System Research Laboratory's (ESRL) Physical Sciences Division (PSD; Dole et al., 2017). The resulting ENRR Field Campaign, led by PSD but involving many partners

within and outside of NOAA, had several observational and research components, including hundreds of atmospheric profiles of temperature, humidity and winds measured by radiosondes launched from Kiritimati (pronounced "Christmas") Island and the NOAA Ship *Ronald H. Brown*. This manuscript documents the collection of these soundings, their reprocessing with improved surface data, the initial quality control applied, and the resulting data sets.

5 **2 Field sites and data collection**

2.1 Kiritimati Island, Republic of Kiribati[1]

The Line Islands lie south of Hawaii, extending from 6.4°N to 11.4°S (Fig. 1). Kiritimati, whose highest point is 13 m ASL and whose land area is 321 km^2, is the largest of these islands (Scott, 1993). About 6,500 residents live in four villages on the northern and western portions of the island (Morate, 2016), while the southern portion is now designated as a bird sanctuary.
10 Physical contact with the outside world is limited; during most of 2016 there were 2 international passenger flights each week, occurring during one round trip between Fiji and Hawaii which stops at Kiritimati in both directions. Most supplies are imported on monthly freight flights from Hawaii and during irregular visits by freighter ships. There is internet access on the island but it is slow, perhaps 0.26 Mbps downloading and 0.03 Mbps uploading on a good day. Some of the best internet connectivity on the island is at the Captain Cook Hotel.

The Captain Cook Hotel, located in the Main Camp neighbourhood of Banana village, was the center of our ENRR operations. The hotel property is located on the northeast-facing coast (Fig. 2) and has hosted NOAA scientists in the past. The grounds are sandy and moderately vegetated, predominantly with short grasses and similar plants but also with some shrubs and coconut palms. The short beach runs steeply down to shallow water that extends for tens of meters to the edge of the reef; beyond that,
20 the reef drops off sharply and the water is hundreds of meters deep. For nine weeks PSD maintained a staff of two observers who occupied both sides of a two-unit bungalow. One of the bungalow's units also housed the computers and radiosonde equipment. Helium tanks were stored on the south corner of the large (13 m by 31 m) concrete pad outside the bungalow. The concrete pad was very slightly higher than the ground on which our bungalow and the surface station sat, but overall the area where observations were collected was flat and fairly level.

Site set-up began on 25 January 2016. A tripod was positioned north of the bungalow and east of the concrete pad, and outfitted with an R.M. Young 5103 anemometer, a tipping bucket rain gauge, a shielded Vaisala HMP45C temperature and relative humidity probe, and a box containing a Vaisala PT101B barometer and a Campbell Scientific CR23X datalogger. Above the box was a solar panel which charged the battery that provided power to the datalogger. This tripod was moved northeast about

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[1] In the Gilbertese (Kiribati) language, "ti" respresents an "ss" sound. Hence, Kiribati is pronounced "KEER-eh-bahss", and Kiritimati is the Gilbertese spelling of "Christmas".

10 m, to a location just above the beach, on 5 February 2016. More details of the surface instrumentation, as well as an explanation of the post-deployment processing of the collected surface observations, are found in Hartten et al. (2017a).

The first Vaisala RS92-SGP radiosonde was launched at 1136 UTC on 26 January 2016. Typically, one observer was primarily
5   responsible for filling the balloon. A flattened tarpaulin tube, held together by a strong Velcro pull-strip running its entire length, was laid on the somewhat sheltered concrete porch outside the bungalow and the 350-gram balloon was laid inside it. The balloon was connected to an analog regulator attached to one of the gas cans and the balloon was filled with approximately 600 PSI of helium, or until the balloon was about the same length as the tube. (We were unable to use lift weights to determine when the balloons were filled because we lacked anything resembling an inflation shed to keep the filling balloon protected
10   from the wind and weather during the process.) The other observer was generally inside the bungalow, using the Vaisala GC25 ground check set (Vaisala Oyj, 2006) and the DigiCORA sounding software (Vaisala Oyj, 2010b; version 3.64.1) to calibrate and initialize the radiosonde and set the sounding parameters. The DigiCORA software was directed to run in "research mode" so that it would continue to collect data during the downward trajectory of the radiosonde after the balloon burst. After the ground check was complete and the battery pack was connected, the radiosonde was usually carried outside
15   and set on the surface station's instrument box, in the shade of the station's solar panel. This provided a well-ventilated location for the radiosonde to equilibrate to outdoor conditions and acquire GPS lock. It also allowed for several minutes of independent pressure, temperature and humidity measurements co-located with the surface meteorological station. When it was time to launch, surface observations from the meteorological station were entered into the DigiCORA software; the radiosonde was attached to the balloon and then released from the concrete pad or the grassy space south of it and west of the
20   bungalow. The coordinates (2.01°N, 157.40°W) adequately describe the location of both the surface station and the area from which the radiosonde was launched.

Our goal was to collect 00 and 12 UTC soundings, so in accordance with WMO guidelines (World Meteorological Organization, 2013; see Part III Section 2.4.10) launches typically occurred 30-45 minutes before the nominal sounding time
25   (i.e. 2315-2330 and 1115-1130 UTC). We monitored the launch from inside the bungalow, and relaunched if the radiosonde did not reach 400 hPa (Office of the Federal Coordinator for Meteorology (OFCM), 2006). This only happened once, with the 7 February 2016 12 UTC sounding. The system had occasional trouble locking on to enough GPS satellites to get position readings, but typically only for short segments of a flight. There were also signal dropouts when the radiosonde was in the null directly over the site's telemetry antenna. After the balloon burst, we continued to monitor the radiosonde until we ceased
30   receiving data. When the data collection finished, we used the DigiCORA software's simulation feature to run the radiosonde transmissions through the software's "non-research" (operational) mode and created TEMP, PILOT, and BUFR messages from the operational-mode sounding data. After we ran a script to apply the proper WMO wrappers to the TEMP messages, the WMO, PILOT, BUFR, and research-mode text files were then compressed into a single file for transmission to Boulder,

Colorado, via the internet access point at the main hotel building. Compression into one file was necessary because the internet was slow and tended to drop the connection after each transfer; even so, we were not always able to get the file to Boulder in the desired time window. Computer scripts in Boulder uncompressed the file and pushed the TEMP message to NOAA's National Center for Environmental Prediction (NCEP) Central Operations for transmission to the Global Telecommunication

5   System (GTS).

While "CXI" is a common abbreviation for Kiritimati and is the International Air Transport Association (IATA) airport code for the local airport, we chose to use "CXENRR" as the station name to clearly distinguish these data from a variety of past meteorological data collections. The ICAO code assigned to Kiritimati is "PLCH", which is used for METAR and other data

10   collected by the Kiribati Weather Service on Kiritimati.

There were two exceptions to the standard launch times. We did an extra launch on 2 March 2016 at 2017 UTC. This involved coordinated transmissions with several amateur radio antennas that were to operate at 3.505 – 28.010 MHz near our bungalow for two weeks, in order to verify that there was no interference with our sounding data collection. The 00 UTC sounding on

15   10 March 2016 was not launched until 0324 UTC (yielding a nominal sounding time of 03 UTC) because of a power failure at the hotel. Over the course of our deployment, we successfully collected 125 soundings.

2.2 NOAA Ship *Ronald H. Brown*

The NOAA Ship *Ronald H. Brown*, part of NOAA's Marine Operations Center – Atlantic (MOC-A) fleet, is a Global Class research vessel that has been in service since 1997. It was scheduled to perform routine servicing of the Tropical Atmosphere

20   Ocean (TAO) array buoys along 140 °W and 125 °W in February and March 2016. These buoys' position within the area of warm SST anomalies associated with the ongoing El Niño motivated a collaborative effort in which the ENRR Field Campaign was able to deploy three scientists and radiosonde equipment on the ship during the cruise. The objective of the ship-based ENRR sounding campaign was to collect atmospheric profiles of temperature, humidity and winds six times per day (at 00, 04, 08, 12, 16, and 20 UTC) at the beginning of the campaign, while the ship travelled from Hawaii southeast to the first

25   scheduled TAO buoy position at (9° N, 140° W); eight times per day (at 00, 03, 06, 09, 12, 15, 18, and 21 UTC) while the ship was near the anomalously warm water between 8° N and 8°S conducting the TAO maintenance (from 140° W to 125° W); and six times per day again during the final leg north to San Diego from (8° N, 125° W). With a few exceptions, we carried out this schedule, collecting 193 profiles from 16 February to 16 March (Fig. 3). This total includes 135 soundings between 8° N and 8° S, as well as three launches in mid-February that were coordinated with dropsondes deployed nearby by the NOAA

30   Gulfstream-IV (G-IV; see Table 1). The G-IV conducted numerous research flights over the tropical Pacific as part of the ENRR field campaign (Dole et al., 2017). During these three launches the shipboard ENRR staff were in close contact with

scientists from the G-IV mission and adjusted their launch times as best they could in order to get nearly coincident launches from ship and plane.

2.2.1 General launch procedures

Launch preparation took place in two adjoining locations on the main deck: in the staging bay just forward of the fantail, and in an air-conditioned lab to port of that bay (Fig. 4). One observer ran the Vaisala RS92-SGP radiosondes through the standard Vaisala ground check and initialization procedure in the small lab. After this, the radiosonde was placed outside in a safe place on the fantail to equilibrate to ambient conditions until just prior to launch. The radiosonde was always put on something that was elevated approximately 1 m above the fantail's deck, and in a location that was as shaded as possible. The equilibration time was several minutes and the radiosonde was determined to be equilibrated when the real-time data feed showed that both the temperature and humidity had stabilized to outside conditions.

While one observer prepared the radiosonde, another was in the staging bay filling the 350-gram latex balloon[2] with helium. The staging bay's roll-down doors face aft, have a 5.5 m vertical clearance, and were open, as was a narrower tall doorway on the starboard side of the staging bay. The bay thus provided incomplete shelter from the wind, with the resulting localized turbulence preventing a direct and consistent measure of lift using weights. Instead, the amount of helium required to achieve the optimum 5 m s^{-1} ascent rate was determined by trial and error based on ascent rate and helium use during previous launches, and in consultation with the ENRR observers on Kiritimati. Finally, the equilibrated radiosonde was brought to the staging bay and attached to the filled balloon; surface observations were entered into the DigiCORA software; there was a final check that the radiosonde's temperature, relative humidity, and pressure were working and that the GPS receiver was in contact with at least four GPS satellites; and then the pair was brought out onto the fantail for launch.

The fantail of the ship typically experiences a substantial amount of turbulence caused by high winds (gusting to 15–20 m s^{-1} free stream) passing through the ship's superstructure. Since the main purpose of this cruise was to exchange TAO buoys in order to restore data, the fantail area was also generally crowded with recovered and not-yet-deployed buoys. Both factors made launches challenging. During the day, the balloon launches had to be coordinated with deck operations on the fantail involving the buoy maintenance. In several cases, this coordination resulted in late launches. At night, the ship was typically underway, which often increased the relative wind speed and local turbulence compared to daytime conditions. Ten to fifteen minutes prior to every launch the bridge was notified of our intent. If the ship was underway, we first checked the relative wind speed and direction to determine if we would ask the bridge to adjust the ship's course and speed to optimize a fantail

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[2] The first sounding, launched on 16 February 2016 at 19:02 UTC from Pearl Harbor, Hawaii, used a 200-gram balloon in order to conserve supplies because it was primarily a demonstration launch. The soundings launched on 28 February 2016 at 20:10 UTC and 2 March 2016 at 02:10 UTC also employed 200-gram balloons as part of experimentation designed to improve our launch success rate.

launch. (Due to the ship's tight schedule, slowing the ship was not always possible.) The actual launch was from whatever position on the fantail that the operators estimated would maximize the likelihood of success.

As at Kiritimati, the DigiCORA software was run in "research mode" and continued to collect data after the balloon burst, stopping only when transmission ceased because of splashdown or loss of signal. The sounding was then simulated in "non-research" (operational) mode. BUFR and TEMP messages were created from the operational mode data using the ship's assigned call sign, "WTEC", and appropriate WMO headers were applied to the TEMP messages. Then both the "research mode" and "non-research mode" sets of text sounding files as well as the BUFR and TEMP messages were uploaded to Boulder, from whence the TEMP messages were pushed to NOAA/NCEP's Central Operations for transmission to the GTS.

Conditions on the fantail resulted in a number of failed launches, for example when swirling winds drove the radiosonde into the superstructure or the ocean. In some cases, we successfully attempted a second launch; in other cases, the sounding was skipped. We had limited supplies of radiosondes, balloons, and helium, so many factors were taken into account in the decision to relaunch: the likelihood of a repeat failure, whether there was sufficient time remaining to collect and send the data before the next launch, and how critical data from this time period was. Of the 206 planned soundings, 13 scheduled launch times (6%) were missed due to failures of the initial launch.

The above descriptions of launch conditions and procedures are likely applicable to RS92 radiosonde launches from NOAA Ship *Ronald H. Brown* during cruises associated with various multi-year programs. These would include AEROSE (Aerosols and Ocean Science Expeditions, Nalli et al. 2011), AMMA (African Monsoon Multidisciplinary Analysis, Lebel et al. 2010), PIRATA (originally Pilot Research Moored Array in the Tropical Atlantic (Servain et al. 1998), now Prediction and Research Moored Array in the Tropical Atlantic (Bourlès et al. 2008)), and the Stratus Project (part of the Eastern Pacific Investigation of Climate (EPIC) program; see de Szoeke et al. 2010 and references). Exceptions would tend to be related to the cruise-specific arrangement of objects on the fantail, and the resulting effects on where radiosondes could be placed while equilibrating and from where they could be launched.

2.2.2 Special conditions and atypical soundings

Solar heating of the fantail deck often increased the air temperature where the radiosonde was equilibrated before daytime launches. We have compared the temperature from the corrected surface meteorology data set (Cox et al. 2017b) to that recorded by the radiosondes on the fantail deck after equilibration but prior to launch. The surface meteorology was collected independently by the ship's standard complement of instruments; instrument details and post-processing are documented in Hartten et al. (2017a). The differences between fantail conditions as measured by the radiosondes during their equilibration time and the contemporaneous post-processed surface data were +0.59° ± 0.6º C during the day (i.e. when solar zenith angle

was less than 90º) compared to +0.04° ± 0.2º C when the sun was below the horizon. There is a corresponding difference in relative humidity (-3.61% ± 3.74% during the day compared to -0.01% ± 1.43% at night). We have made no attempt to change any sounding data based on this information, but are documenting it here for interested researchers.

5   During the cruise, the DigiCORA sounding system experienced problems tracking GPS satellites. Even though it had contact at launch with at least the minimum four satellites required to calculate winds, the station would sometimes lose contact with all satellites after launch. After consulting with Vaisala we determined there was failing hardware in the GPS receiver card within the DigiCORA sounding processing subsystem (SPS220; Vaisala Oyj, 2010a, b). As a result, we collected no wind data in 26 of our soundings; 24 of the affected soundings (Table 2) were launched on 23–27 February 2016. A variety of other
10   issues affected about 10% of the launches (Table 3). Ground checks were occasionally skipped during relaunches because of timing issues; if the sonde didn't go up immediately, by the time the data were collected and formatted the window for uploading the data would be past. Lack of a ground check could affect the temperature and humidity measurements in the final sounding, but any pressure affects should be mitigated by the reprocessing described in Section 3.1. Sometimes visual observation indicated that the spool did not unwind properly or fully after launch. This could lead to unrepresentative
15   measurements caused by the instruments "being too close to the radiation environment of the balloon or … encountering the balloon's wake as it ascends" (OFCM, 2006), or to erroneous winds because the instruments were swinging on a shorter "pendulum" than expected by the software. On a few occasions the radiosonde passed through the ship's exhaust; this is discussed further in Section 3.1. Finally, some balloons were influenced by the flow through the moving ship and its cargo in ways that made the balloon drop perilously close to the water before moving away from the ship and then gaining altitude.
20   We have made no attempt to systematically identify these cases, but users of the data may encounter signs of this in the initial seconds of some soundings.

3 Sounding Correction and Quality Control

3.1 Reprocessing with corrected surface values

The atmospheric soundings collected by these radiosondes are "anchored" by the independent surface pressure, temperature,
25   humidity, and wind values fed to the DigiCORA system during the launch procedure. These surface data become the first level of the sounding profiles and the DigiCORA software uses them as it begins to process the data transmitted from the radiosonde and create the profile. Therefore, the surface observations influence the profile, generally only quite close to the surface for temperature and humidity and approximately throughout the lower 300–400 m for the winds. Surface data are also used at one point in the pre-launch process, when surface pressure is entered during the ground check so the Vaisala GC25 can calibrate
30   the radiosonde's barometer.

At both locations there were two types of issues with the surface data that were entered into the DigiCORA software in the field. First, it was obvious during the campaign that at least some surface instruments were incorrectly calibrated or not well positioned. Second, site staff did not have real-time access to averaged data but had to make their best subjective estimate of representative values to enter, often from on-screen values that were updating at 1Hz. Therefore, the first step in producing research-quality rawinsonde data sets was to correct the archived surface meteorology at both locations, as described in Hartten et al. (2017a). The resulting Kiritimati data (Hartten et al., 2017c) are at two-minute resolution through 11 February 2016 04:05:43 UTC and at one-minute resolution thereafter, while the corrected surface data from the NOAA Ship *Ronald H. Brown* (Cox et al., 2017b) are all at one-minute resolution. With the exception of the pressure data, as explained below, we consider these corrected surface meteorology data appropriate for initializing the research-quality rawinsonde observations.

At CXENRR, the radiosonde ground check occurred within one of the bungalow units, which was typically cooled by an air conditioner set to 20°–25° C. The surface meteorology instrumentation was outside, about 29 m from the Vaisala GC25 until 5 February 2016 21–22 UTC when it was relocated to a position about 39 m away. The barometer height at the surface station's final location was 3.6 m ASL. As the campaign progressed the observers realized they were seeing pressure differences between the radiosonde at the ground-check set and the radiosonde when co-located with the surface station. We attempted to quantify this during the post-deployment data processing by comparing the original station-recorded (not corrected) surface pressure with collocated pressure data from 101 radiosondes (Fig. 5). The mean difference was 0.155 hPa, with the radiosonde pressure lower than the station pressure in spite of the fact that the radiosonde pressure had been set equal to the station pressure during the ground check. This difference would correspond to a height difference of 1.29 m between the GC25 and the station barometer, much greater than the measured[3] difference of 0.03 to 0.09 m. We therefore attribute part of the pressure difference to a height difference between the two locations, but the main part to the pressure from the air-conditioning system that slightly raised the room pressure. As a result, when creating the CXENRR radiosonde data sets documented here, the corrected CXENRR surface pressure described in Hartten et al. (2017a) was decreased by 0.155 hPa before being used as a reference pressure during the ground-check phase of reprocessing each sounding.

A similarly subtle issue with surface pressure occurred on the ship. In the field, the pressure entered into the software during the ground check was from the radiosonde itself while it equilibrated on the fantail. We did this because it was the only available measurement at that moment, but it was inadequate because it was not independent and the radiosonde is re-calibrated during this process. The reprocessing used surface pressure based on measurements from the ship's barometer, a Vaisala PTB330 last calibrated on 29 December 2015 and positioned at 15.24 m on the port side of the bridge. We first adjusted the

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[3] On 28 March 2016 the observers used a tape measure, some clothesline, and the horizontal level within a camera that was mounted on a tripod to twice estimate the height difference between the Vaisala GC25 ground check set and the bottom of the datalogger box on the surface station. The inbound comparison indicated that the GC25 was 0.035 m below the station, while the outbound comparison indicated it was 0.093 m above.

pressure reported by the PTB330 to 3.8 m, the height of the radiosonde ground check set; these became the values in the corrected surface meteorology data set. As documented in Hartten et al. (2017a) flow distortion around the superstructure of the ship made pressures from the PTB330 biased slightly high when the port side of the ship was facing into the wind and slightly low when it was on the lee side. Since the ship passed southbound through the trade winds during the first part of the cruise and northbound back through the trade winds on the return, the bias was generally positive during the first half of the campaign (0.15 ± 0.21 hPa) and negative during the second half (-0.17 ± 0.24 hPa). We developed a correction as a function of relative (with respect to the ship's heading) wind direction and applied it to the height-adjusted PTB330 pressures (i.e. to the WTEC corrected surface pressures described in Hartten et al. (2017a)). We used the resulting time series during the radiosonde reprocessing, both as calibration inputs for the radiosonde ground checks and as surface observations. When there was insufficient data available to make the bias correction, the average bias (1.1 hPa) observed in the radiosonde pressure sensors during the campaign was used to calibrate the radiosonde sensor. For additional details on the handling of ship surface pressures, see Hartten et al. (2017a).

After the surface data from both sites were corrected and the surface pressures subjected to the further adjustments described above, all soundings were reprocessed using the simulation feature of Vaisala's DigiCORA sounding software (Vaisala Oyj, 2010a, b; version 3.64.1). The pressure, temperature, humidity, and winds, which would be entered as surface values during a real-time pre-launch process, instead came from the corrected surface meteorology data (plus the additional pressure corrections for CXENRR and for WTEC) at the time closest to launch. For WTEC soundings, initial position information came from the radiosonde, if available, valid at the listed time; otherwise, position information was from the corrected surface data set. The corrected surface winds for WTEC are based on true (earth-relative) winds. These were measured winds which were adjusted by the onboard Science Computer System (SCS) to account for the ship's speed over ground, course over ground, and heading, but not for pitch, roll, and yaw. We viewed this as a more appropriate choice than ship-relative winds because ENRR's focus was the atmosphere's large-scale response to the strong El Niño and we therefore wanted soundings that were representative of the area in which the radiosondes were launched. Reprocessing was done using the standard "non-research" mode that is employed for operational synoptic soundings, and thus was only applied to the data collected as the balloons ascended (Vaisala Oyj, 2010b). This mode corrects for solar radiation effects as well as for the pendulum motion of the instrument package below the balloon, and also performs some interpolation across small data gaps and some undefined filtering.

The effects of the interpolation and filtering in one particular situation can be seen in Fig. 6. The ship's log book identified three soundings for which it appeared that the radiosonde passed through the ship's exhaust shortly after launch (Table 3); this feature is evident in the raw data, but there is no thermal signature in the final data files. We therefore performed a second simulation of those soundings in the "research" mode, which corrects for solar radiation and pendulum effects but otherwise

"is designed to produce data that is edited as little as possible, because it is intended for research use only" (Vaisala Oyj, 2010b). Processing through the "research" mode leaves intact a temperature spike in the lowest 100 m of each sounding, but running the DigiCORA software in "non-research" mode removed the temperature spikes associated with the ship's exhaust.

3.2 Automated quality control

5   After the reprocessing, all soundings were subjected to automated quality control using ASPEN (Atmospheric Sounding Processing ENvironment) software (University Corporation for Atmospheric Research (UCAR), 2016; version 3.3-265), which largely served to remove large random errors in the data. ASPEN The software was run with the "upsonde-1s" parameter settings, except for those settings related to GPS or satellites. ASPEN removed data that failed objective QC checks; smoothed the wind, pressure, temperature, and relative humidity; recomputed geopotential height; and computed the radiosonde ascent

10   rate (Martin 2007). This post-processing with ASPEN satisfies the quality-control aspects of what Ciesielski et al. (2012) define as a "Stage 2" or "Level 2" sounding data sets. While an assessment of the quantitative changes and uncertainties associated with the reprocessing described in section 3.1 and the quality control performed by ASPEN could be of interest to some segments of the user community, exploring that issue is beyond the scope of our objective. Such an analysis more naturally proceeds from the development of "Level 3" sounding data, which has been examined and corrected for systematic

15   errors (bias). Ciesielski et al. (2012) includes a discussion of random and systematic errors in modern thermodynamic soundings in that context, and contains citations to several relevant studies.

However, users need to be aware that automated quality control removes some but not all "bad" or "unrepresentative" data. For instance, RS92-SGP radiosondes contain two pulse-heated humidity sensors, both of which are reconditioned during the

20   ground-check procedure (Vaisala Oyj, 2015). Data generally flows from them alternately. If the two sensors are for some reason giving realistic but different readings, large step-like swings in humidity are possible. These swings may be very obvious (Fig. 7a) or be followed by failure of both sensors (Fig. 7b). Sometimes the problem is clearly intermittent (Fig. 7d), and other times it is harder to discern whether it is intermittent or pervasive (Fig. 7c). While these swings may be obvious to the human eye and look non-meteorological, they do not trigger anything in ASPEN's automated quality control and are not

25   removed. Situations like these would be systematically identified in the more time-consuming and person-intensive process of creating what Ciesielski et al. (2012) term "Level 3" and "Level 4" data sets.

4 Characteristics of the data sets

4.1 Soundings from Kiritimati Island

The 125 rawinsonde soundings from Kiritimati span nominal times 26 January 2016 12 UTC to 28 March 2016 00 UTC. The

30   27 February 2016 00 UTC sounding launch was timed to be as coincident in time and space as possible with a dropsonde

launched from the NOAA G-IV during one of its near-equator missions (Table 1). Height coverage of the CXENRR soundings was very good (Table 4, Fig. 8). Ninety-four percent of the soundings reached the Cold-Point Tropopause (CPT), defined here as the lowest temperature in the profile (Selkirk 1993, Highwood and Hoskins 1998) that occurs above 15 km and with at least 2 km of sounding data above the level with lowest temperature. The minimum height criteria was designed to prevent flagging

5   the top of a short sounding; because it is more than 1 km below the mean CPT heights found at Truk (7.44° N, 151.83° E) by Mehta et al. (2011) we consider it unlikely that we are falsely identifying a Lower Tropopause (LT, Mehta et al. 2011) or other inversion below the CPT. Near-equatorial zonal winds at 40 hPa are used to define the phase of the quasi-biennial oscillation (QBO, e.g. Baldwin et al. 2001), and 88% of the Kiritimati soundings reached that level. The Kiritimati soundings (Fig. 8, Fig. 9a) clearly show the complex layers of easterlies and westerlies observed in the Singapore soundings during early 2016

10   (c.f. Fig. 2 in Newman et al. 2016) as well as downward propagating wave activity (reviewed in Baldwin et al. 2001).

For the observers on Kiritimati, the most notable atmospheric feature of our stay was the rainfall; our surface station recorded 0.938 m of rain, nearly as much as the long-term annual average observed at the Kiribati Meteorological Service's Kiritimati station. Most of that rain (69%) came during 6 major events that were associated with the Intertropical Convergence Zone

15   (ITCZ). The driest soundings (e.g. 7 March 2016 at 00 UTC, shown in Fig. 10) had only 0.04 m of precipitable water vapour and featured a deep very dry layer in the mid-troposphere with a temperature inversion at the base. This deep dry layer appears to be associated with the strong high pressure system located between Hawaii and the California/Baja coast; in similar synoptic settings, the sharply bounded dry upper-troposphere was also observed by dropsondes from the G-IV. At Kiritimati, profiles like this frequently contained incursions of marginally wetter air, such as seen in Fig. 10a just below 300 hPa and between

20   400–500 hPa. The wettest soundings were collected when the ITCZ was over or very near the island (e.g. 22 March 2016 at 12 UTC, Fig. 11) and measured as much as 0.08 m of precipitable water vapour, with saturated or nearly saturated conditions extending up to the middle of the troposphere. In this instance, with the high centered near 35° N, the ITCZ extended west of 160°W and was analyzed directly over Kiritimati at 12 UTC. From 1010–1759 UTC on 22 March 2016, our station at Kiritimati recorded 75 mm of rainfall.

25   **4.2 Soundings from the NOAA Ship *Ronald H. Brown***

There are 193 rawinsonde observations from the NOAA Ship *Ronald H. Brown*; the nominal time of the first was 16 February 2016 19 UTC and of the last was 16 March 2016 12 UTC. Three were launched to coincide with nearby dropsondes from the G-IV (Table 1). Height coverage was also very good at this station (Table 4, Fig. 12), with 89% of the radiosondes reaching the CPT and 87% reaching 40 hPa. When viewed in a simple time-height section (Fig. 12), the ability to identify lower-

30   stratospheric phenomena is complicated by the ship's movement into, through, and out of the near-equatorial zone. However, the stacked easterlies/westerlies/easterlies observed at Kiritimati (Fig. 9a) and at Singapore (Newman et al. 2016) are clearly present in early- to mid-March 2016 (Fig. 9b), and fine-scale descending waves are evident in the lower stratosphere above

about 20 km through much of the cruise (Fig. 12). The ship's soundings captured a wide variety of conditions, including extremely dry layers between 300 and 500 hPa (Fig. 13a, collected when the ship was north of the ITCZ and on the edge of the northern hemisphere subtropical high) and strongly capped marine boundary layers (Fig. 13b) in the northern parts of the cruise, as well as deep tropical moisture nearer the equator (Fig. 13c, d).

5 Data Availability and Use

NOAA's National Center for Environmental Information (NCEI) is the archival location for these ENRR data sets. The DOIs are as follows: Level 2 rawinsonde data from Kiritimati (doi:https://doi.org/10.7289/V55Q4T5K), Level 2 rawinsonde data from the NOAA Ship *Ronald H. Brown* (doi:https://doi.org/10.7289/V5X63K15). The data sets, together with sample code to read them and skew-T plots extending to 100 hPa, are also available from NOAA/ESRL/PSD at https://www.esrl.noaa.gov/psd/enso/rapid_response/data_pub/. Users of these data must cite the appropriate DOI and reference the data as indicated below:

Cox, C., D. Wolfe, L. Hartten, and P. Johnston: El Niño Rapid Response (ENRR) Field Campaign: Radiosonde Data (Level 2) from the NOAA Ship Ronald H. Brown, February-March 2016 (NCEI Accession 0161527), Version 1.1, NOAA /National Centers for Environmental Information, doi:https://doi.org/10.7289/V5X63K15, 2017.

Hartten, L., P. Johnston, C. Cox, and D. Wolfe: El Niño Rapid Response (ENRR) Field Campaign: Radiosonde Data (Level 2) from Kiritimati Island, January-March 2016 (NCEI Accession 0161525), Version 1.1, NOAA /National Centers for Environmental Information, doi:https://doi.org/10.7289/V55Q4T5K, 2017.

Each data set is comprised of many separate files, one for each sounding. The files are in the NASA Ames Format for Data Exchange ("NASA-Ames Format") which is written in plain (ascii) text, making it highly portable to different computers and easily accessible to users who have limited computer resources. Detailed explanations of the format are found in Gaines and Hipskind (1998) and at the Centre for Environmental Data Analysis (CEDA)British Atmospheric Data Centre (BADC) website (Centre for Environmental Data AnalysisBritish Atmospheric Data Centre, 2002). NASA-Ames Format requires certain metadata in various header sections and provides for additional optional headers; we have endeavored to take advantage of this aspect to make each file self-describing. It also requires that the total number of header lines be the first number in the first line of the file, and that the data following the header lines be space-delimited. Our files use the last header line to provide rudimentary column headers for the data that follow, to make it easier to import the data into spreadsheets or to quickly examine them by eye. Time is the independent variable in each file and is given in seconds since launch time. Users working with the data from Kiritimati Island, especially those interacting with residents and local meteorological data collections, may want to be aware that in terms of civil time Kiritimati is in the Line Island Time (LINT) time zone (UTC+14).

6 Conclusions

The ENRR Field Campaign, conducted in January–March 2016 during a very strong El Niño event, included a wide variety of special intensive observations. Among those were frequent radiosonde launches from Kiritimati Island (2.0°N, 157.4°E) and from the NOAA Ship *Ronald H. Brown* during its cruise along the near-equatorial TAO buoy transects at 140° W and

5 125° W. One radiosonde from Kiritimati and three from the ship were launched in coordination with dropsonde releases from the NOAA Gulfstream-IV (G-IV; see Table 1), which conducted numerous research flights over the tropical Pacific as part of the ENRR field campaign (Dole et al., 2017).). This resulted in four pairs of radiosonde and dropsonde soundings, each pair separated in (horizontal) launch location by only 28–54 km and launched within a 5–8 minute window.

10 We have reprocessed 125 soundings from Kiritimati and 193 from the ship, using corrected surface pressure for the radiosonde calibration and corrected surface meteorology as the first point of the sounding. We then subjected them to automated quality control via NCAR's ASPEN software. ASPEN removed and flagged values that failed objective checks, smoothed the wind, pressure, temperature, and relative humidity profiles; recomputed geopotential height; and computed the radiosonde ascent rate. We have written the resulting data to NASA-Ames format (ASCII) files, incorporating rich metadata in the header together with mandated information. The results are what Ciesielski et al. (2012) define as a "Stage 2" or "Level 2" sounding

15 data sets: data in a uniform, digital, easily read format which have been processed with automated quality-control checks to remove bad values. While both sites also collected the data reported by the radiosondes as they fell after balloon burst, only the data collected during radiosonde ascent have been reprocessed and included in these data sets.

20 The Kiritimati data set consists of 9.5 weeks of twice-daily soundings in the midst of this El Niño episodes warm Central Pacific waters. Since 82% of the soundings reached at least 30 hPa, these data show a portion of the unusual 2015-2016 QBO as well as the incursions of the ITCZ which led to nearly a meter of rainfall during our deployment. Data from the four-week cruise of the NOAA Ship *Ronald H. Brown* include 8 soundings per day during the 19 days spent at 8° N – 8° S between 140° W and 125° W. Height coverage was comparable to that at Kiritimati, with 83% reaching 30 hPa. The ship soundings captured

25 lower-stratospheric features of the QBO and also sampled a variety of tropical marine tropospheric settings. The data from both sites should be useful for a variety of research studies and reanalyses of the structure and impact of the strong 2015/16 El Niño event.

Author Contributions. All authors spent at least two weeks at Kiritimati or four weeks aboard the ship launching radiosondes.

30 C. J. Cox, P. E. Johnston, and D. E. Wolfe reprocessed soundings from Kiritimati and the NOAA Ship *Ronald H. Brown* in consultation with L. M. Hartten; P. E. Johnston applied ASPEN to the reprocessed soundings. L. M. Hartten assembled metadata and created the file headers with input from all co-authors, then created the final files. L. M. Hartten prepared the manuscript with input from all co-authors.

Competing Interests. The authors declare that they have no conflict of interest.

Acknowledgements. The ENRR Field Campaign was funded by NOAA through the Office of Oceanic and Atmospheric
Research (OAR) as well as the National Weather Service (NWS), the Office of Marine and Aviation Operations (OMAO) and
the National Environmental Satellite, Data and Information Service (NESDIS). We thank the Republic of Kiribati for allowing
NOAA to conduct research on Kiritimati Island, and the Kiribati Meteorological Service for engaging with our observers. The
crew of the NOAA Ship *Ronald H. Brown*, in particular Captain R. Kamphaus, NOAA/OMAO Survey Technicians J. Gunter
and M. Bradley, and NOAA/OMAO Lieutenant A. Hopper, were very supportive of our staff and operations. On Kiritimati,
the management and staff of the Captain Cook Hotel welcomed ENRR into their lives (helium canisters and all) and made our
work and stay very pleasant, while J. Bryden's logistical support and supplies were critical to our observational success. We
extend our thanks to P. E. Ciesielski (Colorado State University) for pre-and post-deployment conversations about quality
assurance and quality control; to T. Schiffbauer and W. Otto (PSD) for ensuring both crews had balloons and helium; to T.
Coleman (CIRES and PSD) and D. Gottas (PSD) for their work on making real-time file transfer a reality; to C. A. Smith
(CIRES and PSD) for plotting our soundings in real time and later helping shepherd the data through the archival process; and
to D. Hooper (CIRES and PSD) for the scripts which transformed the post-processed data into final form and which enable
users to browse skew-T plots of them on a web page. We appreciate G. Wick's (PSD) and O. Persson's (CIRES and PSD)
careful reading of and though-provoking comments about the manuscript. VGF files for the surface analyses were provided
by R. Tanabe of NOAA/NWS Pacific Region Headquarters and very kindly turned into maps by W. D. Plummer of
NOAA/National Centers for Environmental Prediction (NCEP) Central Operations.

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Climate Prediction Center (CPC) and International Research Institute for Climate and Society (IRI): El Niño/Southern Oscillation (ENSO) Diagnostic Discussion, El Niño/Southern Oscillation (ENSO) Diagnostic Discussion:
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Figures

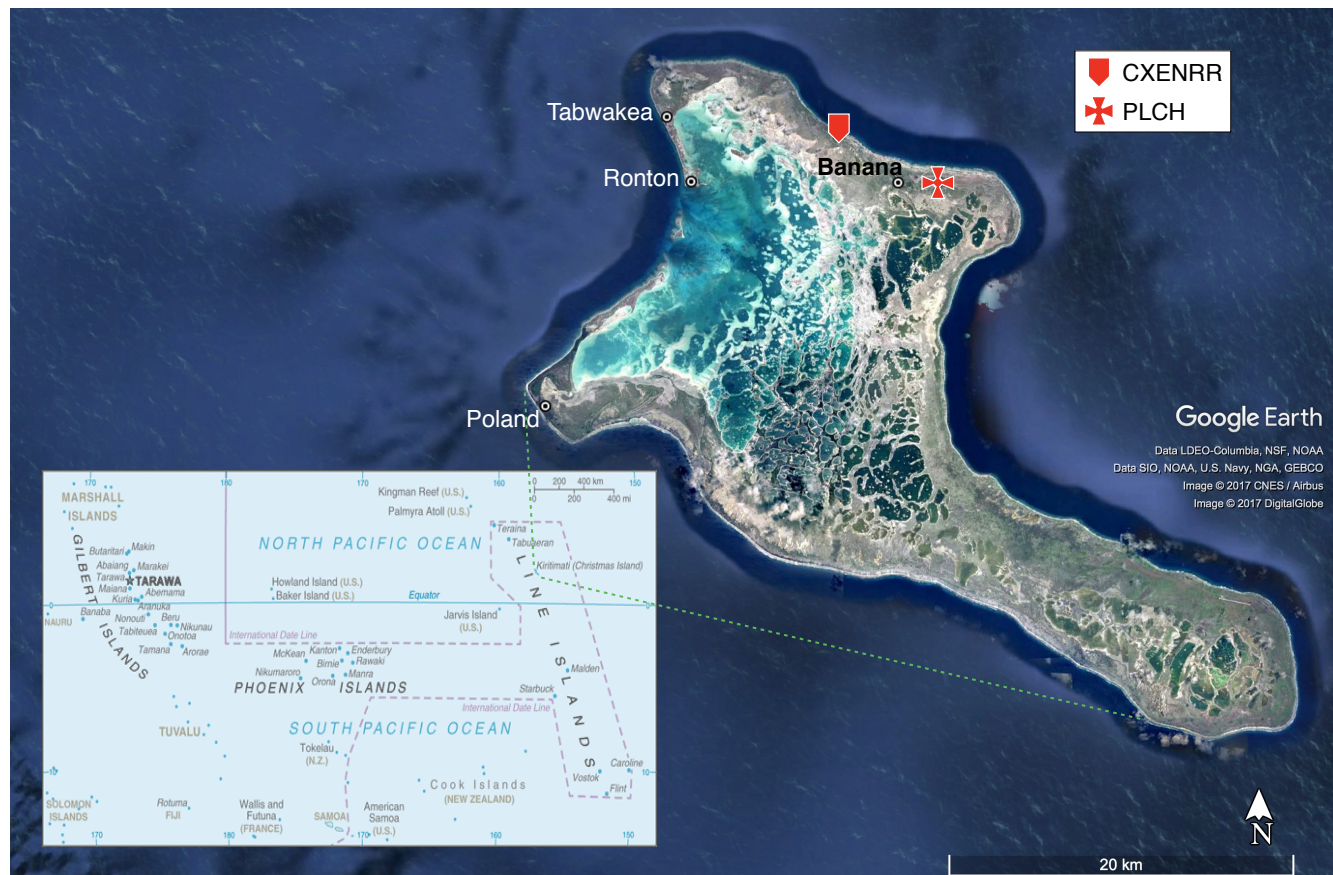



Figure 1: Composite satellite photo of Kiritimati showing the location of the four population centres, Cassidy International Airport (International Civil Aviation Organization (ICAO) airport code PLCH), and the ENRR field site (CXENRR). The inset map shows Kiritimati's location within the Line Islands and the Republic of Kiribati in general. Kiribati map by the U.S. Central Intelligence Agency courtesy of the University of Texas Libraries, The University of Texas at Austin. Station symbol colours from www.ColorBrewer.org by Cynthia A. Brewer, Geography, Pennsylvania State University.

Figure 2: Aerial view of the Captain Cook Hotel property on Kiritimati Island, including the CXENRR site (upper left). The final location of the surface meteorology instruments is at the base of the pin symbol, north-northeast of the bungalow that housed staff and the Vaisala DigiCORA sounding system. The concrete pad where the helium tanks were stored and from which balloons were launched runs northwest to southeast, ending just north of the bungalow. The main hotel building used for internet access is southeast of the CXENRR site.

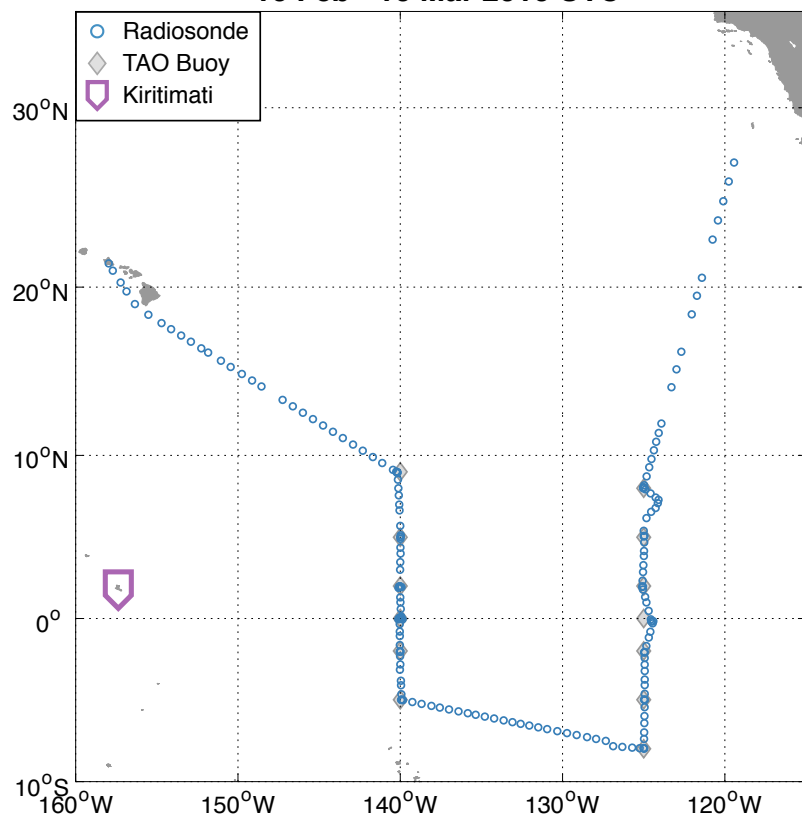



Figure 3: The release locations of all rawinsonde observations collected by the NOAA Ship *Ronald H. Brown* during ENRR, 16 February – 16 March 2017. Colours from www.ColorBrewer.org by Cynthia A. Brewer, Geography, Pennsylvania State University.

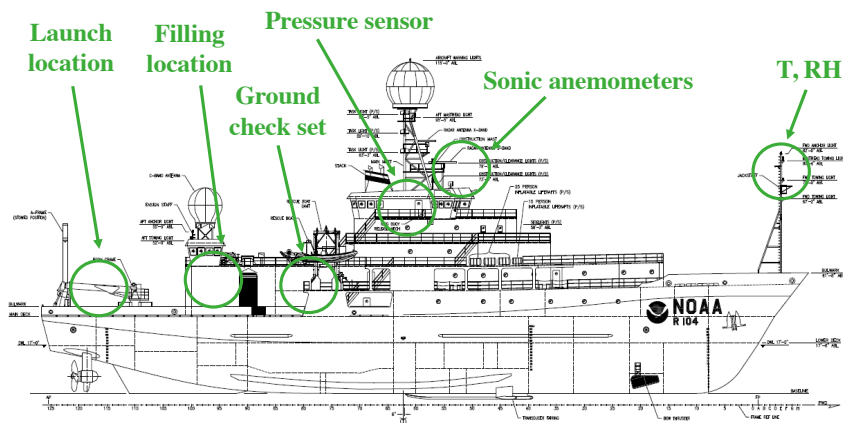



Figure 4: Schematic of the NOAA Ship *Ronald H. Brown* annotated to show the location of key surface meteorological instruments as well as the staging bay where the balloons were filled and the approximate location of the fantail, where they were launched. Annotation colours from www.ColorBrewer.org by Cynthia A. Brewer, Geography, Pennsylvania State University.

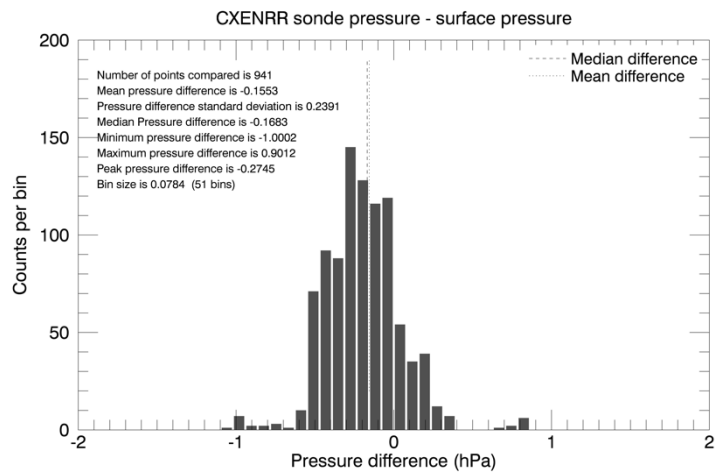



Figure 5: The distribution of the difference between one-minute average Kiritimati radiosonde pressures and one-minute average surface pressures when the radiosonde was co-located with the surface instruments prior to launch. All available data from 101 distinct radiosondes are included.

Soundings through the exhaust plume of the NOAA Ship *Ronald H. Brown*
(post-processed with corrected surface meteorology)

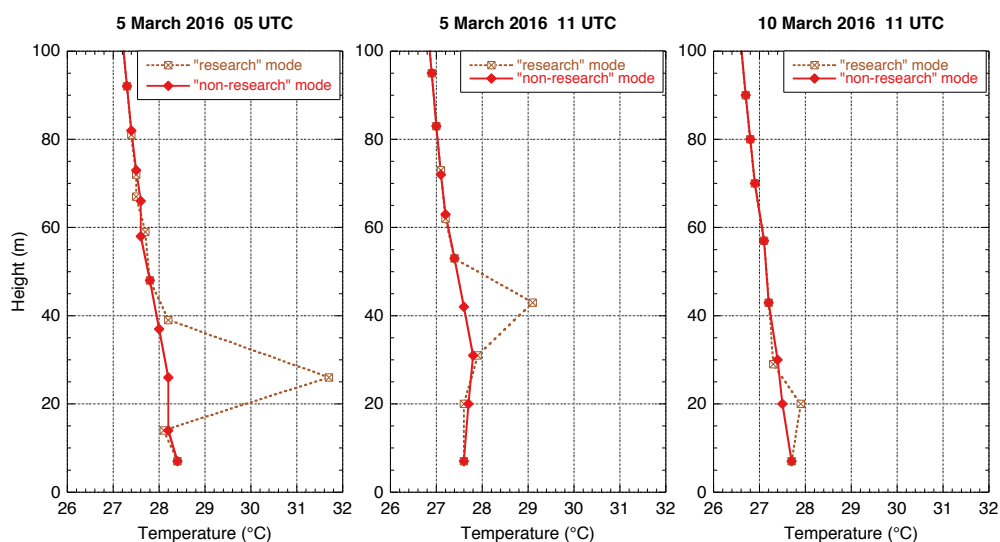



Figure 6: A comparison of "research mode" and "non-research mode" DigiCORA processing on temperature soundings believed to have been collected as the radiosonde passed through the exhaust plume of the NOAA Ship *Ronald H. Brown*. The "non-research mode" soundings were used in the creation of the data sets described in the text. Data colours from www.ColorBrewer.org by Cynthia A. Brewer, Geography, Pennsylvania State University.

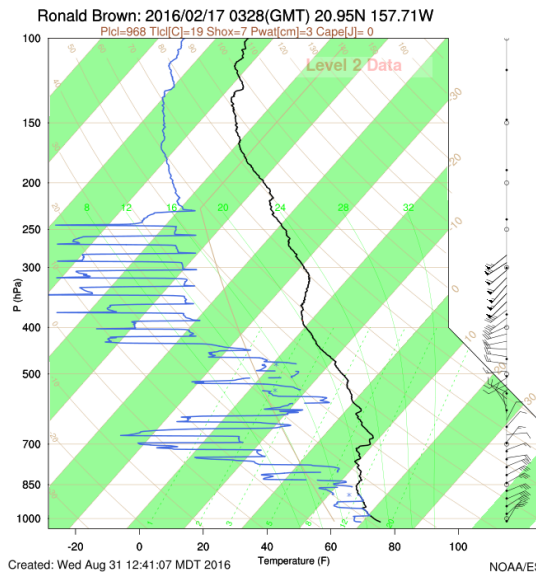
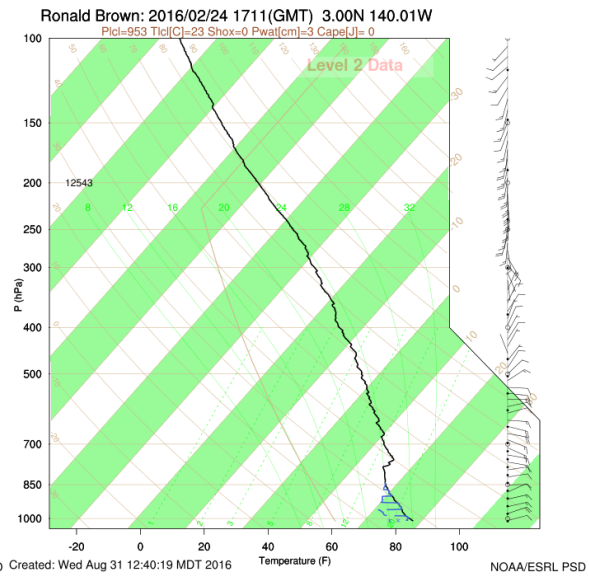
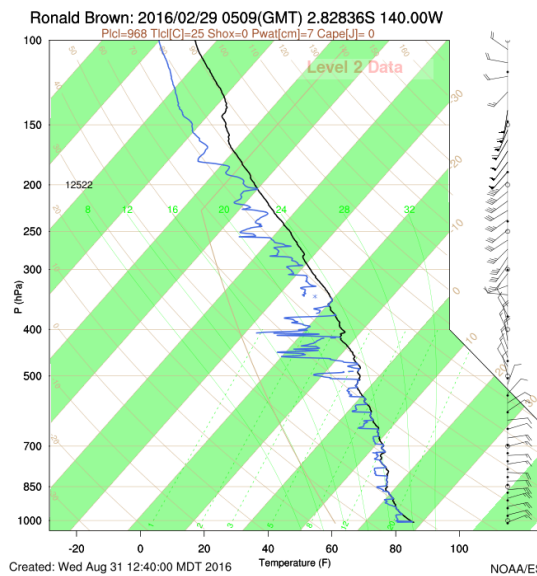
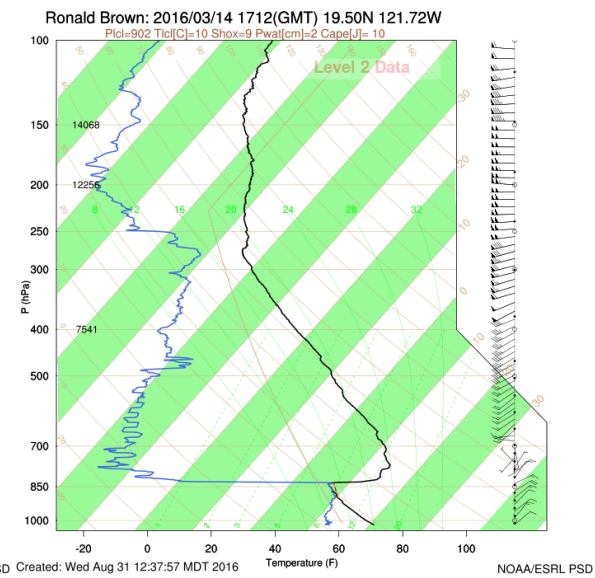



Figure 7: Examples of soundings with humidity issues that pass through ASPEN automated quality control.

Soundings at CXENRR during ENRR
26 Jan - 28 Mar 2016 UTC

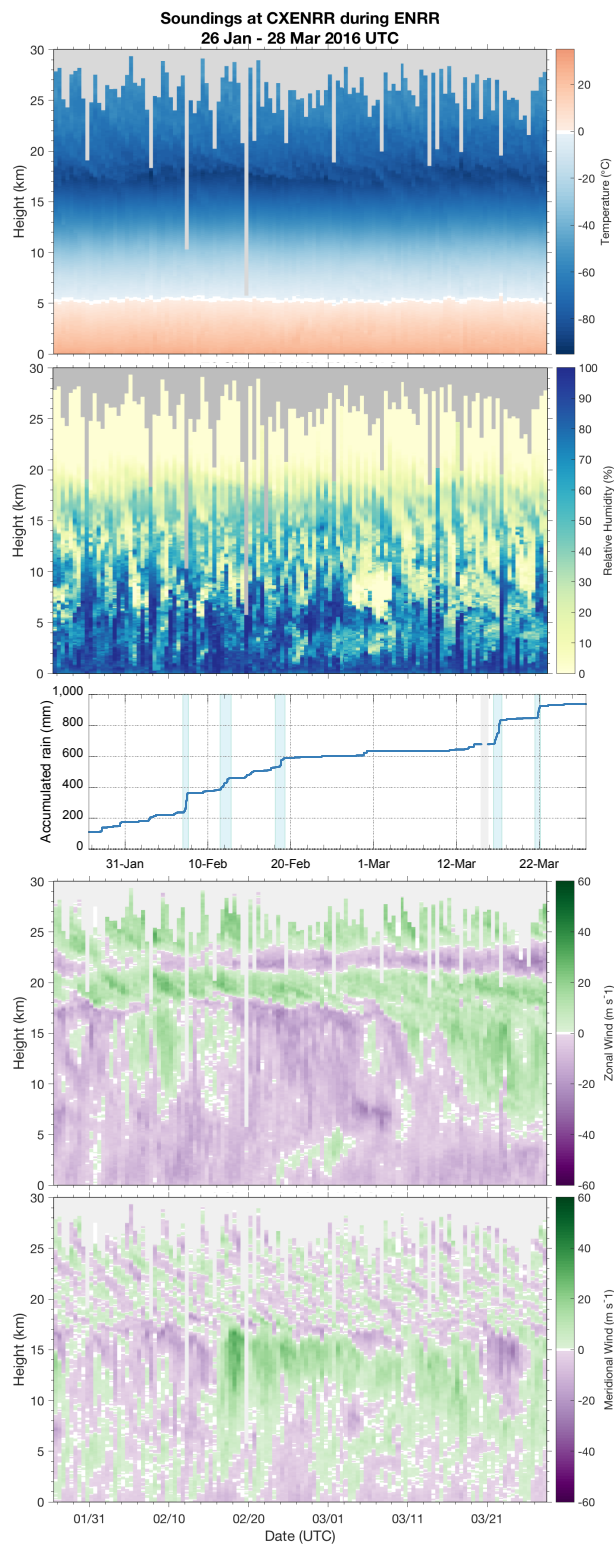
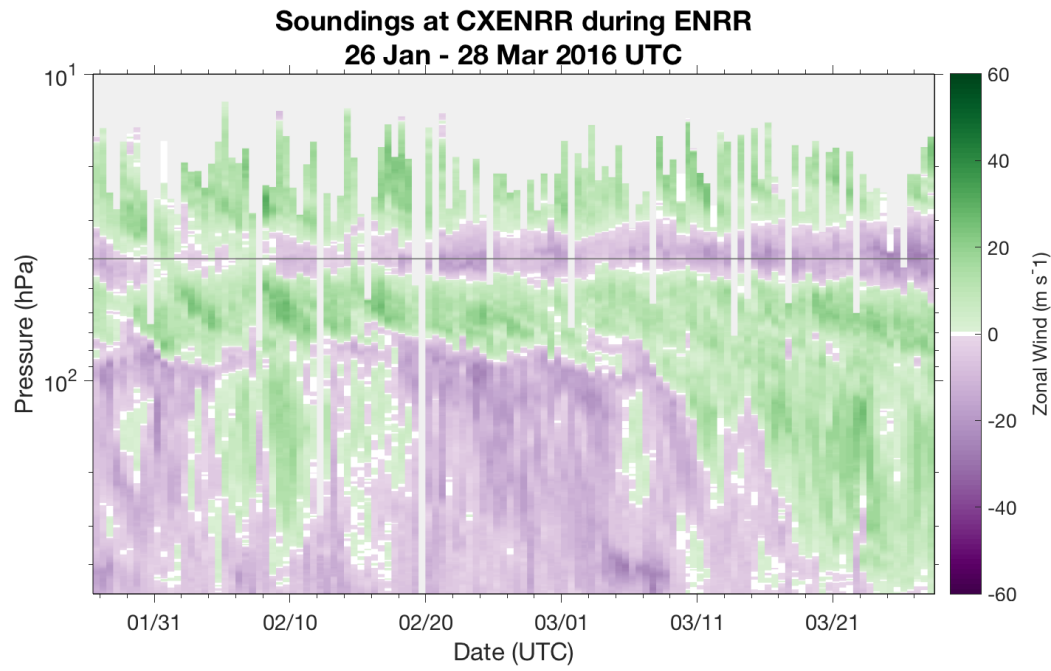
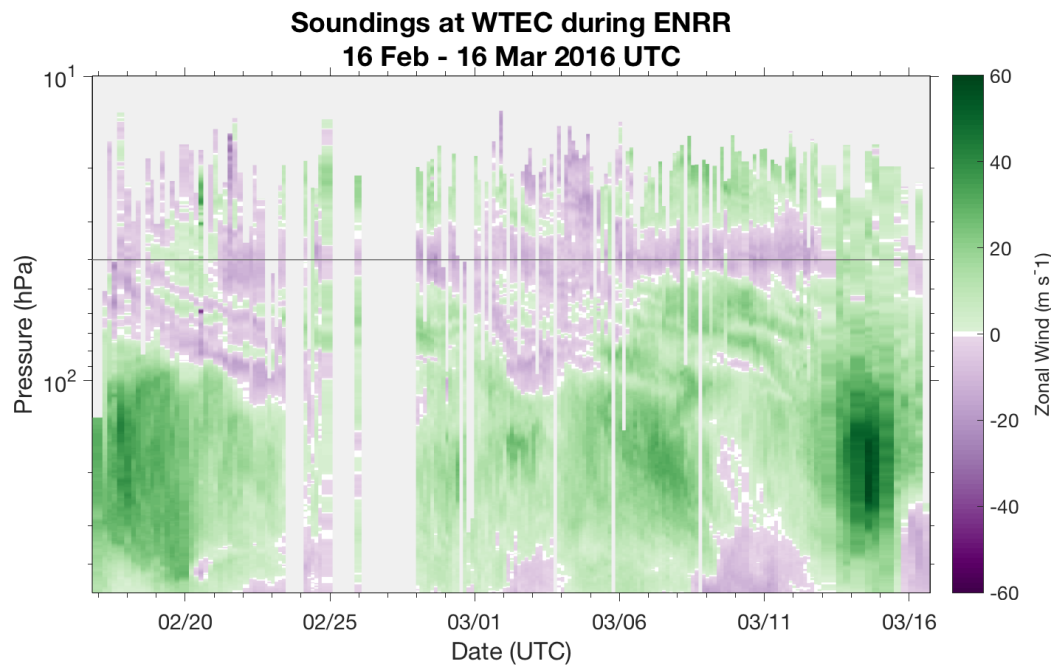



Figure 8: Vertical time-height sections of the temperature, relative humidity, and wind components measured by radiosondes launched from Kiritimati, together with the accumulated precipitation during the deployment (middle panel, shown only during the time range matching the time-height sections). Data from each sounding has been interpolated to a 25-m vertical grid before plotting and stretches along the x-axis to completely fill the time between launches, while grey shading indicates no available data. The time between the penultimate and final launch is duplicated in the plotting of that final launch. On the accumulated precipitation panel, light blue bars indicate the times of the major rain events that occurred during the sounding observation interval; the initial major rain event occurred before the first sounding was launched. Colours from www.ColorBrewer.org by Cynthia A. Brewer, Geography, Pennsylvania State University.

a)

b)

5   **Figure 9: Zonal winds in the upper troposphere and lower stratosphere during ENRR, as measured by radiosondes launched from a) Kiritimati and b) the NOAA Ship *Ronald H. Brown*. Colours from www.ColorBrewer.org by Cynthia A. Brewer, Geography, Pennsylvania State University.**

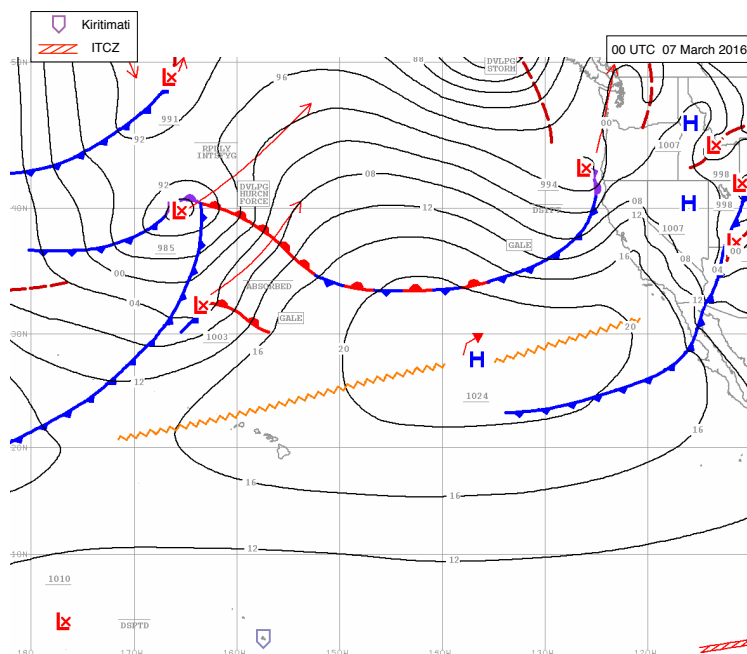
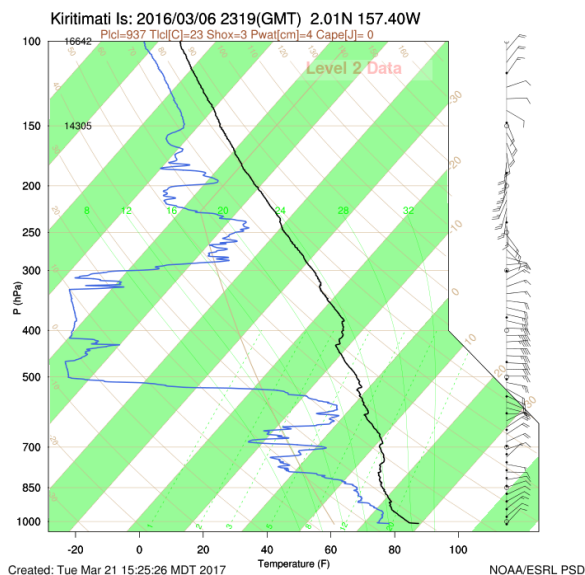



Figure 10: The 7 March 2016 00 UTC sounding, which featured extremely dry air between 300–500 hPa, was the driest one collected at CXENRR. A coincident surface analysis shows a strong subtropical high pressure system east-northeast of Hawaii and the northern hemisphere ITCZ confined to the furthest east regions of the Pacific, leaving Kiritimati Island (2.0° N, 157.4° W) and the rest of the central equatorial Pacific in a broad zonal band of weak surface pressure gradient.

Figure 11: The 22 March 2016 12 UTC sounding, the wettest one collected at CXENRR, was launched while the ITCZ was located over Kiritimati Island.

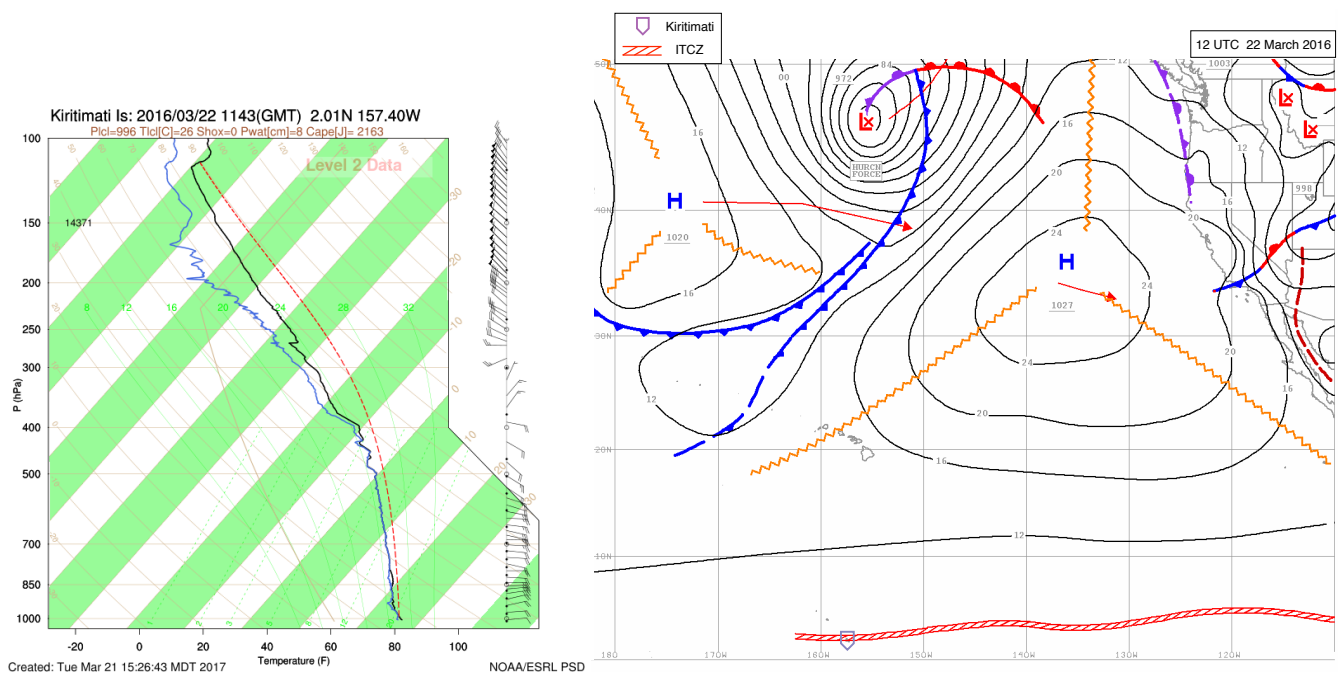
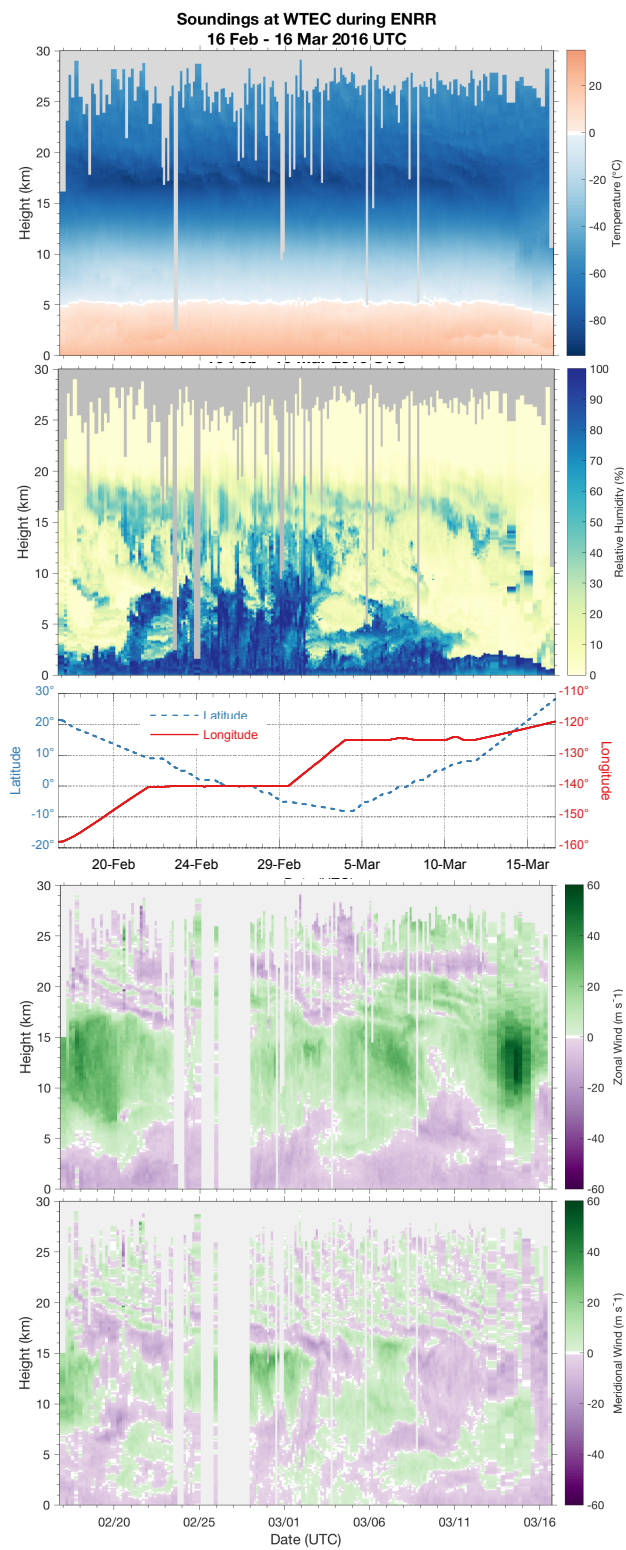



Figure 12: Vertical time-height sections of the temperature, relative humidity, and wind components measured by radiosondes launched from the NOAA Ship Ronald H. Brown, together with the ship's position (middle panel). Data from each sounding has been interpolated to a 25-m vertical grid before plotting, and stretches along the x-axis to completely fill the time between launches. The time between the penultimate and final launch is duplicated in the plotting of that final launch. Grey shading indicates no available data. Colours from www.ColorBrewer.org by Cynthia A. Brewer, Geography, Pennsylvania State University.

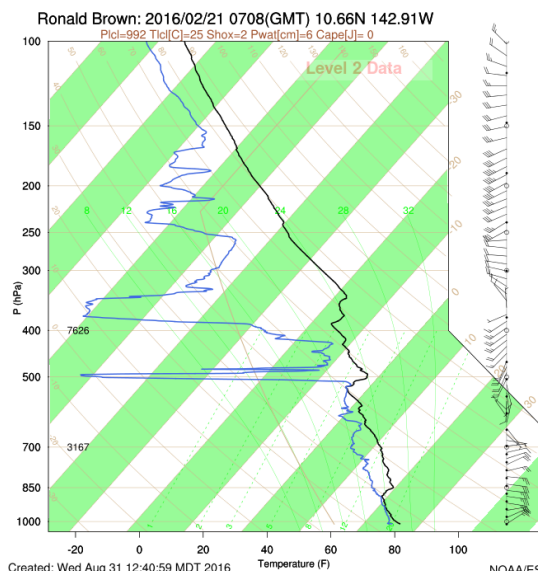
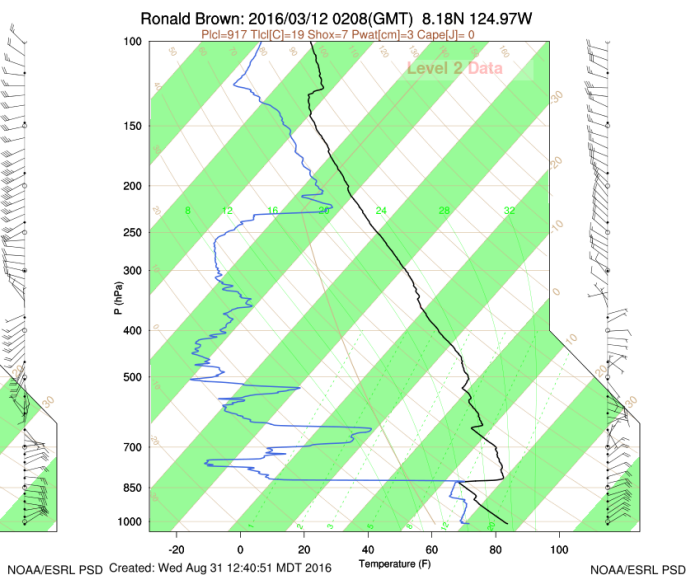
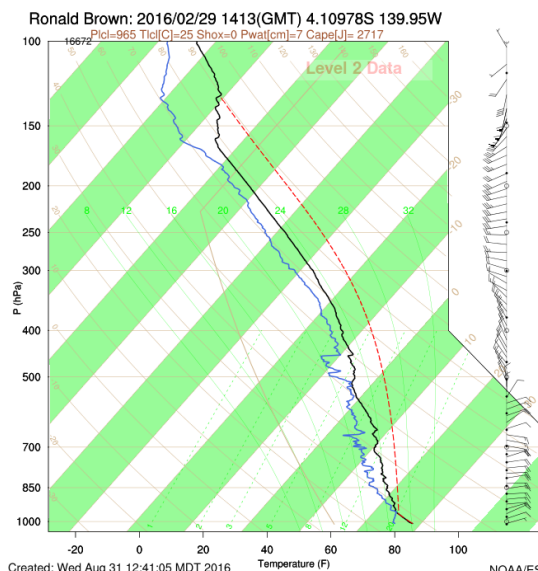
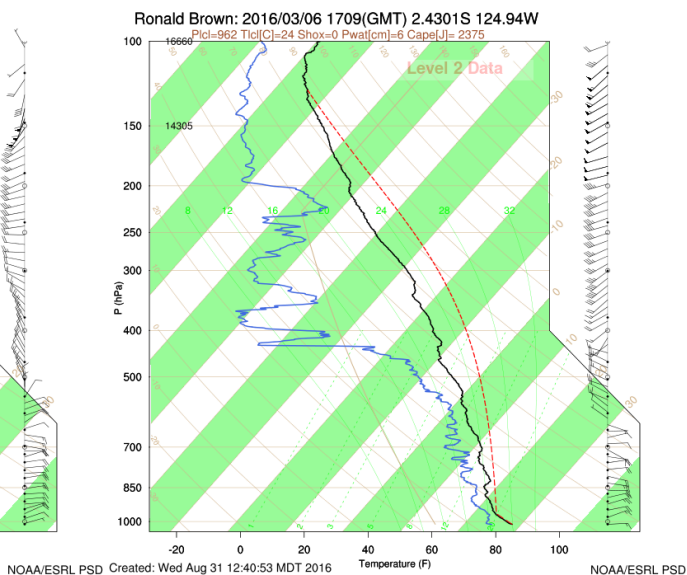



Figure 13: Examples of tropospheric conditions captured by soundings taken from the NOAA Ship Ronald H. Brown during ENRR.

Tables

TABLE 1. Coordinated soundings during the ENRR Field Campaign. Radiosondes were launched from either the ship or the island, and dropsondes were released from the NOAA Gulfstream-IV (G-IV). The horizontal distance between launch points was calculated using Great Circle navigational formulae by the NOAA/National Hurricane Center calculator at http://www.nhc.noaa.gov/gccalc.shtml.

NOAA Ship Ronald H. Brown							
Radiosonde			**Dropsonde**			**Time**	**Distance**
Nominal time	**Release time**	**Release location**	**Release location**	**Release time**	**Flight**	**between**	**between**
17 February 2016 20 UTC	17 February 2016 21:32 UTC	18.39° N 155.52° W	18.22° N 155.72° W	17 February 2016 21:26 UTC	RF12	00:06	28 km
18 February 2016 22 UTC	18 February 2016 22:01 UTC	16.42° N 152.26° W	16.21° N 151.80° W	18 February 2016 21:53 UTC	RF13	00:08	54 km
22 February 2016 00 UTC	21 February 2016 23:46 UTC	9.12° N 140.45° W	9.00° N 140.01° W	21 February 2016 23:51 UTC	RF14	00:05	50 km
Kiritimati							
Radiosonde			**Dropsonde**			**Time**	**Distance**
Nominal time	**Release time**	**Release location**	**Release location**	**Release time**	**Flight**	**between**	**between**
27 February 2016 00 UTC	26 February 2016 23:19 UTC	2.01° N 157.40° W	1.99° N 157.04° W	26 February 2016 23:26 UTC	RF15	00:07	40 km

TABLE 2. ENRR Soundings from the NOAA Ship *Ronald H. Brown* which contain no winds due to GPS issues.

Nominal time	Release time	Release location
23 February 2016 18 UTC	23 February 2016 17:18 UTC	5.70° N, 140.00° W
23 February 2016 20 UTC	23 February 2016 20:10 UTC	5.13° N, 139.97° W
24 February 2016 00 UTC	23 February 2016 23:16 UTC	5.03° N, 139.98° W
25 February 2016 2 UTC	25 February 2016 2:13 UTC	1.98° N, 140.03° W
25 February 2016 5 UTC	25 February 2016 5:14 UTC	1.98° N, 140.01° W
25 February 2016 8 UTC	25 February 2016 8:20 UTC	1.89° N, 140.11° W
25 February 2016 11 UTC	25 February 2016 11:06 UTC	1.94° N, 139.92° W
25 February 2016 14 UTC	25 February 2016 14:08 UTC	1.97° N, 140.07° W
25 February 2016 17 UTC	25 February 2016 16:44 UTC	1.96° N, 140.07° W
26 February 2016 2 UTC	26 February 2016 2:12 UTC	1.30° N, 140.00° W
26 February 2016 5 UTC	26 February 2016 5:08 UTC	1.00° N, 139.99° W
26 February 2016 8 UTC	26 February 2016 8:07 UTC	0.59° N, 139.97° W
26 February 2016 11 UTC	26 February 2016 11:11 UTC	0.12° N, 139.94° W
26 February 2016 14 UTC	26 February 2016 14:07 UTC	0.00° N, 139.95° W
26 February 2016 17 UTC	26 February 2016 17:04 UTC	0.02° N, 139.96° W
26 February 2016 20 UTC	26 February 2016 20:11 UTC	0.02° N, 139.95° W
26 February 2016 23 UTC	26 February 2016 23:06 UTC	0.03° N, 140.00° W
27 February 2016 2 UTC	27 February 2016 2:17 UTC	0.03° N, 139.96° W
27 February 2016 5 UTC	27 February 2016 5:10 UTC	0.04° N, 139.97° W
27 February 2016 8 UTC	27 February 2016 8:11 UTC	0.05° S, 140.12° W
27 February 2016 11 UTC	27 February 2016 11:14 UTC	0.05° S, 139.86° W
27 February 2016 14 UTC	27 February 2016 14:10 UTC	0.04° N, 140.06° W
27 February 2016 18 UTC	27 February 2016 17:35 UTC	0.03° N, 139.97° W
27 February 2016 20 UTC	27 February 2016 20:16 UTC	0.03° N, 140.03° W
29 February 2016 12 UTC	29 February 2016 11:21 UTC	3.83° S, 139.96° W
3 March 2016 17 UTC	3 March 2016 17:13 UTC	7.29° S, 128.49° W

TABLE 3. ENRR Soundings from the NOAA Ship *Ronald H. Brown* with other known issues.

Nominal time	Release time	Release location
Bad Relative Humidity Sensor(s)		
17 February 2016 03 UTC	17 February 2016 03:28 UTC	20.95° N, 157.71° W
24 February 2016 17 UTC	24 February 2016 17:11 UTC	3.00° N, 140.01° W
29 February 2016 05 UTC	29 February 2016 05:09 UTC	2.83° S, 140.00° W
13 March 2016 00 UTC	12 March 2016 23:09 UTC	11.93° N, 123.91° W
14 March 2016 18 UTC	14 March 2016 17:12 UTC	19.50° N, 121.72° W
No Ground Check		
18 February 2016 22 UTC	18 February 2016 22:01 UTC	2.83° S, 140.00° W
25 February 2016 20 UTC	25 February 2016 20:20 UTC	1.98° N, 140.01° W
29 February 2016 00 UTC	28 February 2016 23:45 UTC	2.04° S, 140.00° W
29 February 2016 12 UTC	29 February 2016 11:21 UTC	3.83° S, 139.96° W
8 March 2016 17:23 UTC	8 March 2016 17:22 UTC	1.95° N, 125.09° W
Spool Not Properly Unwound		
21 February 2016 19 UTC	21 February 2016 19:12 UTC	9.54° N, 141.11° W
29 February 2016 08 UTC	29 February 2016 08:14 UTC	3.15° S, 140.02° W
3 March 2016 02 UTC	3 March 2016 02:17 UTC	6.69° S, 131.50° W
3 March 2016 20 UTC	3 March 2016 20:11 UTC	7.40° S, 127.93° W
8 March 2016 02 UTC	8 March 2016 02:08 UTC	0.05° S, 124.56° W
9 March 2016 05 UTC	9 March 2016 05:04 UTC	2.86° N, 125.04° W
12 March 2016 02 UTC	12 March 2016 02:08 UTC	8.18° N, 124.97° W
12 March 2016 05 UTC	12 March 2016 05:09 UTC	8.72° N, 124.82° W
Balloon Passed Through Ship Exhaust		
5 March 2016 05 UTC	5 March 2016 05:05 UTC	7.00° S, 124.97° W
5 March 2016 12 UTC	5 March 2016 11:10 UTC	6.00° S, 124.95° W
10 March 2016 12 UTC	10 March 2016 11:11 UTC	6.18° N, 124.83° W

TABLE 4. Gross characteristics of the ENRR sounding data sets from Kiritimati and the NOAA Ship *Ronald H. Brown*.

	Kiritimati Island	**NOAA Ship *Ronald H. Brown***
Successful soundings	125	193
Soundings reaching: the tropopause	117 (94%)	171 (89%)
40 hPa	110 (88%)	167 (87%)
30 hPa	103 (82%)	161 (83%)
25 hPa	86 (69%)	141 (73%)
25 km	84 (67%)	139 (72%)