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Article

The Operational Use and Assessment of a Layered Precipitable Water Product for Weather Forecasting

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ABSTRACT

Operational forecasters have a variety of new research products and tools to interrogate precipitation systems for different environments and precipitation regimes. One such product is satellite-derived, column-total precipitable water retrieved in discrete layers as an experimental product developed by the Cooperative Institute for Research in the Atmosphere (CIRA), and transitioned by the National Aeronautics and Space Administration's Short-term Prediction, Research, and Transition Center to numerous weather forecast offices (WFOs) to address specific forecast issues. In 2013 the CIRA layered precipitable water (LPW) product was formally assessed by National Weather Service WFOs in Alaska, the West Coast of the United States, and San Juan, Puerto Rico. Forecasters used LPW to address forecast challenges associated with atmospheric rivers, convective storms, and other types of precipitation events across diverse forecasting domains ranging from marine zones to complex topography. This paper describes the use of LPW by operational forecasters at their WFOs and shows the impact LPW had on precipitation forecasting, as determined by assessment results. During 72 formal user feedback submissions and multiple assessment periods, 62.5% of forecasters had high confidence in LPW. Fifty percent stated that LPW had a "large" impact on their decision process, and another 22.2% said LPW had "some" impact. For 76.4% of the events surveyed, forecasters stated that LPW had "large" to "very large" value over traditional total precipitable water products. Individual case examples will provide a context for forecasters' evaluation of the product in their county warning area.

1. Introduction

The National Aeronautics and Space Administration (NASA) and National Oceanic and Atmospheric Administration (NOAA) testbeds and proving grounds are providing operational forecasters with the opportunity to integrate new satellite information into their forecast process to improve the issuance of forecasts or warning information to the public (Goodman et al. 2012; Ralph et al. 2013). NASA's Short-term Prediction, Research, and Transition (SPoRT) Center (Jedlovec 2013) was created in 2003 to support the use of new, experimental products that are derived from NASA data by the operational weather community. More recently, SPoRT has expanded its focus to transition proxy products for future NOAA satellite sensors to better prepare forecasters for operational use of the new data and products. SPoRT matches experimental datasets and products with forecast problems that are of high priority to operational collaborators and formally assesses their impact by acquiring feedback through assessment periods. Feedback from these assessments guides the research community to further improve their products, as necessary, or to pursue full transition of the product to 24/7 production and distribution to a wider audience. SPoRT transition and assessment activities have already led to advances in the application and use of

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satellite remote sensing for improved diagnostic analysis of weather processes, situational awareness, and nowcasting capabilities by weather forecasters across the country (Darden et al. 2010; Medlin et al. 2012; Zavodsky et al. 2013a, 2013b; Stano et al. 2014).

One such experimental product recently transitioned by SPoRT is the Cooperative Institute for Research in the Atmosphere (CIRA) layered precipitable water (LPW) product, developed by Forsythe et al. (2015). The CIRA LPW uses passive microwave brightness temperatures and ancillary data to separate the columnar total precipitable water (TPW, Kidder and Jones 2007) values into discrete layers. The product combines the Microwave Integrated Retrieval System (MIRS) sounding data produced operationally at NOAA/NESDIS (National Environmental Satellite, Data, and Information Service) from the NOAA-18, NOAA-19, Metop-A, and DMSP F-18 satellites, as well as the version 6 retrievals from the Atmospheric Infrared Sounder (AIRS) on the NASA Earth Observing System (EOS) Aqua satellite made available via the NASA Land Atmospheric Near real-time Capability for EOS system. The microwave data are quality controlled within the respective MIRS and AIRS processing, and satellite swaths from both datasets are projected onto a 16-km Mercator grid using CIRA's Data Processing and Error Analysis System (Jones and Vonder Haar 2002). Intercalibration is not currently employed in this version of the product to allow a visual evaluation of each sensor's performance. The evolution of the product likely will include data from the operational Joint Polar Satellite System being deployed by NOAA (Lee et al. 2010). Coverage for LPW is near-global, and the product is updated with new swath information every 3 h, with the newest satellite swaths overlaying older ones. At the time of this assessment series, the transitioned LPW suite included a column-integrated TPW product as well as LPW layers including the surface–850 hPa, 850–700 hPa, 700–500 hPa, and 500–300 hPa. LPW provides forecasters with increased spatial and temporal information regarding the three-dimensional structure of precipitable water as a supplement to the over-land radiosonde network of observations available twice per day. In particular, LPW provides increased detail in the vertical distribution of precipitable water for data-void regions upstream from the user's area of interest. LPW complements other water vapor data sources, such as the blended TPW product and numerical weather prediction forecasts/analyses, with some benefits such as: (i) LPW provides observations of the middle- and upper-level moisture that is not well represented by the operational blended TPW product; and (ii) LPW is independent of model output and uses all available data from each sensor, in contrast to model data assimilation schemes that may thin data or reject cloudy radiances. Moreover, TPW derived from the *Geostationary Operational Environmental Satellite* (*GOES*) imager is not available as of the *GOES-N* mission owing to the removal of a 12-µm channel in lieu of the 13.36-µm channel. Other applications are described in Forsythe et al. (2015), which explains the development of LPW and serves as part 1 of this paper.

Assessments of LPW were conducted over 6–8-week periods in daily operations with user feedback collected via an online form as events warranted, and these activities were focused on three differing geographic areas. The first of these involved collaboration with the National Weather Service (NWS) Weather Forecast Offices (WFOs) in Eureka (EKA) and Monterey, California (MTR), and Medford, Oregon (MFR), who evaluated the product during their heavy precipitation season (March–April 2013). A second area included NWS WFOs in Anchorage (AFC), Fairbanks (AFG), and Juneau (AJK), and the Alaska Pacific River Forecast Center (APRFC), which evaluated the product from 15 July to 15 September 2013. Both the West Coast and Alaska areas have complex terrain and broad offshore marine zones within their areas of responsibility that make it difficult to efficiently analyze the variations in precipitable water and determine potential quantitative precipitation forecast (QPF) amounts. The LPW product supports offshore analysis of precipitable water in data-void regions, supplementing land-based, upper-air soundings, to better predict significant precipitation events. For example, atmospheric rivers of moisture originating from tropical marine regions are estimated to be responsible for >90% of moisture transport into the mid-latitudes (Zhu and Newell 1998; Ralph et al. 2006; Ralph and Dettinger 2011). Atmospheric river features are at least 400-km wide and sometimes thousands of km long, and they contain at least 2 cm (0.78 in) of vertically integrated precipitable water. The vertical structure of precipitable water associated with an atmospheric river is difficult to analyze over ocean areas owing to the lack of in-situ observations. Water vapor imagery and other imagery products derived from the *GOES* imager only provide information in the mid-to-upper atmosphere and they do not fully characterize the vertical structure of moisture

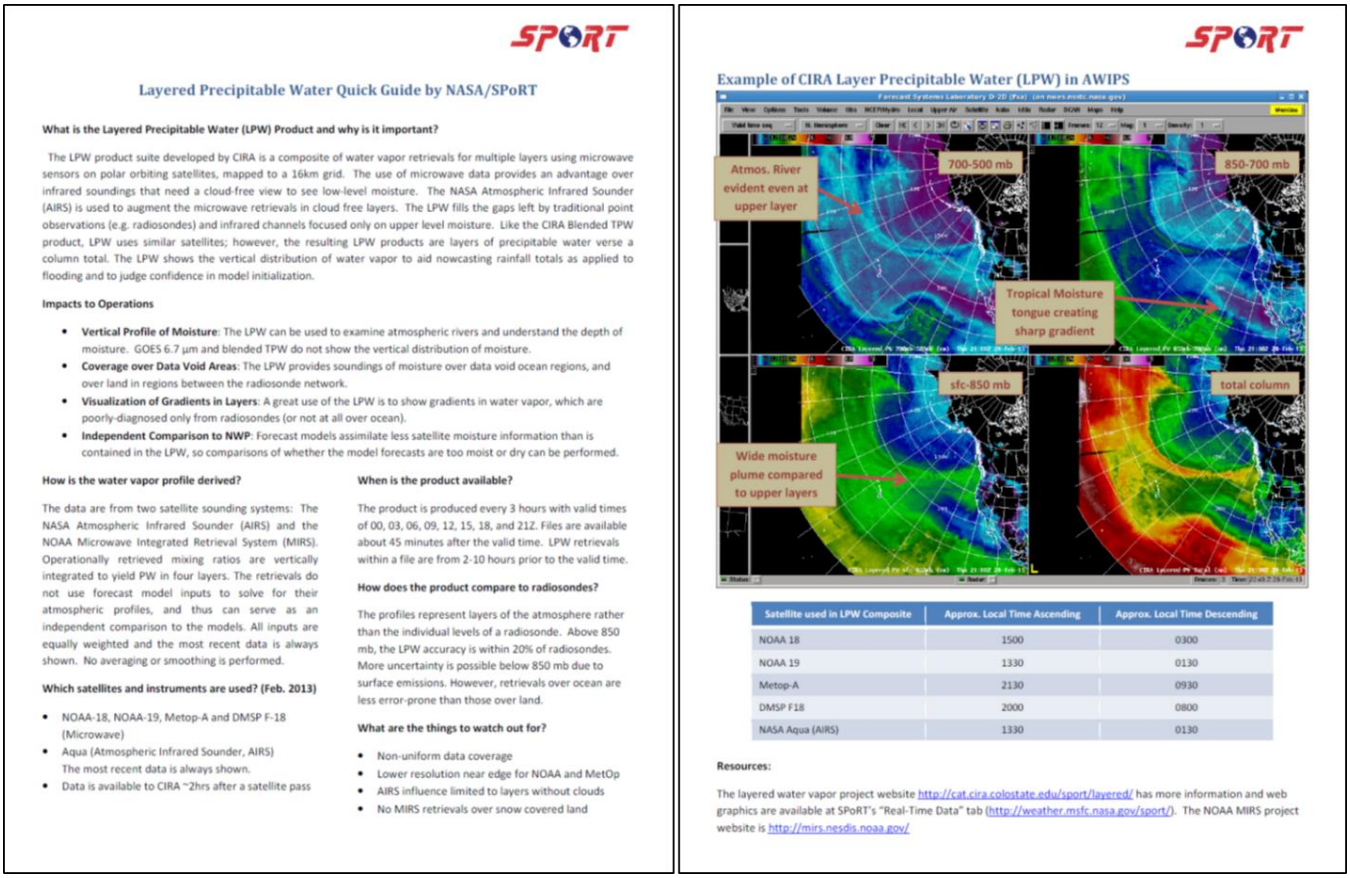
associated with the atmospheric river, and neither *GOES* sounder nor *GOES* imager are available globally. Knowing the vertical distribution of precipitable water is vital when atmospheric rivers or other moisture features interact with elevated terrain along coastal areas and within complex mountain topography. Precipitation associated with atmospheric rivers is subject to orographic enhancement and can cause significant flooding events in coastal environments (Ralph and Dettinger 2011). For this reason, LPW was evaluated by forecasters during atmospheric river events and other high-impact precipitation events in Alaska and along the West Coast where both marine and intermountain regimes exist.

For the third area, the NWS WFO in San Juan, Puerto Rico (SJU), evaluated LPW from 15 July to 15 September 2013 during the region's convective season. In contrast to the United States West Coast and Alaska, the tropical regime of Puerto Rico often experiences higher values of TPW. Intense, convective rains of the tropical regime, combined with the complex topography of Puerto Rico, frequently lead to dangerous flash flooding of shallow rivers across the island. While easterly tropical waves can be tracked via water vapor imagery, and TPW data can be used to monitor the columnar precipitable water, the LPW product indicates how precipitable water in these systems is interacting with elevated terrain to enhance potential precipitation amounts throughout the SJU county warning area (CWA).

The similarity of forecast challenges among the geographically distant forecast areas allowed an opportunity to investigate the value of CIRA LPW in vastly different environments. The successful demonstration of the utility of this product in these diverse locations will provide forecaster confidence in its broader use at additional WFOs when addressing these and other forecast issues (Forsythe et al. 2015). These assessments were the first formal evaluations of LPW among operational forecasters. Results of this study show the impact LPW had on the operational forecast process for the analysis of precipitable water for atmospheric river, convective, and orographically enhanced precipitation events. Section 2 describes the assessment methods and pertinent characteristics of this particular series of assessments. Section 3 discusses the interpretation of assessment data via case examples provided by forecasters during the assessment. Section 4 summarizes the impact of LPW in the operational setting as determined by assessment results.

2. Data and methods

To evaluate the impact of the CIRA LPW product on the aforementioned forecast challenges, NASA-SPoRT conducted a formal assessment of this product by soliciting written feedback on the product's use in operations. The primary goal of this assessment was to determine the value of this product suite—either alone or in conjunction with existing products—for characterizing the vertical distribution of precipitable water over data-sparse regions during high-impact precipitation seasons. Forecasters assessed the impact of the product during precipitation events as a supplement to radiosondes or model analyses of water vapor in data-sparse regions. The assessment approach followed a paradigm established by SPoRT and described by Jedlovec (2013), including the development and delivery of training, soliciting of feedback from forecasters, and summary of results. The participants in the forecast offices were provided teletraining sessions led by CIRA LPW developers (Forsythe and Kidder), and could reference that training locally as needed. They also were given a single-sheet, double-sided "Quick Guide" of highlights from the teletraining materials to use as a reminder during operations (Fig. 1). In parallel to training activities, SPoRT supported the processing and delivery of the CIRA LPW product suite for proper display in the user's decision support system [i.e., the Advanced Weather Interactive Processing System (AWIPS)]. During the assessment period forecasters were encouraged to fill out "Two-Minute Feedback" assessment forms on the NASA-SPoRT webpage (weather.msfc.nasa.gov/sport/survey/) during any weather event to provide both positive and negative feedback on the products. Most questions are provided in a five-point Likert scale format (Likert 1932) for clarity and brevity (Table 1). This style of question provides multiple-choice responses on what can be interpreted as a balanced scale—ranging from positive to negative (e.g., "Product was very useful" to "Product was not useful at all"). The questions gathered information pertaining to the training provided, timeliness and/or availability of the products, forecasters' confidence in the products, the utility of the products in data-sparse regions, and synergistic use of LPW with other operational products. Specific case examples or issues were communicated to SPoRT and product developers by forecasters via the open response section of the Two-Minute Feedback form. Supplemental information or graphics were submitted



SPORT

Layered Precipitable Water Quick Guide by NASA/SPoRT

What is the Layered Precipitable Water (LPW) Product and why is it important?

The LPW product suite developed by CIRA is a composite of water vapor retrievals for multiple layers using microwave sensors on polar orbiting satellites, mapped to a 16km grid. The use of microwave data provides an advantage over infrared soundings that need a cloud-free view to see low-level moisture. The NASA Atmospheric Infrared Sounder (AIRS) is used to augment the microwave retrievals in cloud free layers. The LPW fills the gaps left by traditional point observations (e.g. radiosondes) and infrared channels focused only on upper level moisture. Like the CIRA Blended TPW product, LPW uses similar satellites; however, the resulting LPW products are layers of precipitable water verse a column total. The LPW shows the vertical distribution of water vapor to aid nowcasting rainfall totals as applied to flooding and to judge confidence in model initialization.

Impacts to Operations

- **Vertical Profile of Moisture**: The LPW can be used to examine atmospheric rivers and understand the depth of moisture. GOES 6.7 µm and blended TPW do not show the vertical distribution of moisture.
- **Coverage over Data Void Areas**: The LPW provides soundings of moisture over data void ocean regions, and over land in regions between the radiosonde network.
- **Visualization of Gradients in Layers**: A great use of the LPW is to show gradients in water vapor, which are poorly-diagnosed only from radiosondes (or not at all over ocean).
- **Independent Comparison to NWP**: Forecast models assimilate less satellite moisture information than is contained in the LPW, so comparisons of whether the model forecasts are too moist or dry can be performed.

How is the water vapor profile derived?

The data are from two satellite sounding systems: The NASA Atmospheric Infrared Sounder (AIRS) and the NOAA Microwave Integrated Retrieval System (MIRS). Operationally retrieved mixing ratios are vertically integrated to yield PW in four layers. The retrievals do not use forecast model inputs to solve for their atmospheric profiles, and thus can serve as an independent comparison to the models. All inputs are equally weighted and the most recent data is always shown. No averaging or smoothing is performed.

Which satellites and instruments are used? (Feb. 2013)

- NOAA-18, NOAA-19, Metop-A and DMSP F-18 (Microwave)
- Aqua (Atmospheric Infrared Sounder, AIRS)
  The most recent data is always shown.
- Data is available to CIRA ~2hrs after a satellite pass

When is the product available?

The product is produced every 3 hours with valid times of 00, 03, 06, 09, 12, 15, 18, and 21Z. Files are available about 45 minutes after the valid time. LPW retrievals within a file are from 2-10 hours prior to the valid time.

How does the product compare to radiosondes?

The profiles represent layers of the atmosphere rather than the individual levels of a radiosonde. Above 850 mb, the LPW accuracy is within 20% of radiosondes. More uncertainty is possible below 850 mb due to surface emissions. However, retrievals over ocean are less error-prone than those over land.

What are the things to watch out for?

- Non-uniform data coverage
- Lower resolution near edge for NOAA and MetOp
- AIRS influence limited to layers without clouds
- No MIRS retrievals over snow covered land

SPORT

Example of CIRA Layer Precipitable Water (LPW) in AWIPS

Satellite used in LPW Composite	Approx. Local Time Ascending	Approx. Local Time Descending
NOAA 18	1500	0300
NOAA 19	1330	0130
Metop-A	2130	0930
DMSP F18	2000	0800
NASA Aqua (AIRS)	1330	0130

Resources:

The layered water vapor project website http://cat.cira.colostate.edu/sport/layered/ has more information and web graphics are available at SPoRT's "Real-Time Data" tab (http://weather.msfc.nasa.gov/sport/). The NOAA MIRS project website is http://mirs.nesdis.noaa.gov/

Figure 1. The front and back of the LPW Quick Guide provided to forecasters to reference during operations (PDF available online at weather.msfc.nasa.gov/sport/training/). The front describes the product's perceived impact to operations, availability, input data, and caveats for usage. The back shows an example of the product for an atmospheric river case study. *Click image for an external version; this applies to all figures hereafter.*

Table 1. List of assessment questions answered by forecasters during the assessment period.

Please indicate if you have seen/used basic training materials on the Layered Precipitable Water (LPW) product:
Indicate timeliness of product application for operations:
1. Indicate the precipitation mode/synoptic regime(s) present during this time period:
2. Rank the impact of the LPW on the forecast process:
3. Rate your confidence level in LPW values:
4. Were the TPW values of the layers (separate product) compared to model initialization/forecasts of TPW to gauge accuracy of total moisture?
5. How would you rate the value of having this LPW product compared to a standard TPW product?
6. Other feedback about these products can be written here:

by forecasters in separate email attachments during follow-up discussions between SPoRT staff and operational forecasters to obtain additional feedback. Participants also were encouraged to submit and review examples on the Wide World of SPoRT blog (nasasport.wordpress.com/) to show examples of the operational use of experimental products and to provide additional peer-to-peer training.

The participating offices used LPW to address a variety of forecasting challenges related to precipitation. For the regions of interest in this assessment, observed precipitation events were characterized by forecasters as mostly convective and/or terrain-influenced. When grouped into regions, the precipitation regimes examined in the Alaskan offices were mostly terrain-influenced and/or stratiform; events in SJU were mostly convective; and events in the West Coast were most often described as offshore/incoming (Fig. 2). Note that forecasters could choose more than one precipitation regime for a single event (e.g., both terrain-influenced and stratiform). The sparse number of precipitation events in the West Coast resulted in fewer surveys taken overall during their two-month assessment period, but five forecasters contributed to the assessment (Table 2.). Forecasters in SJU contributed an assessment for almost every precipitation event that

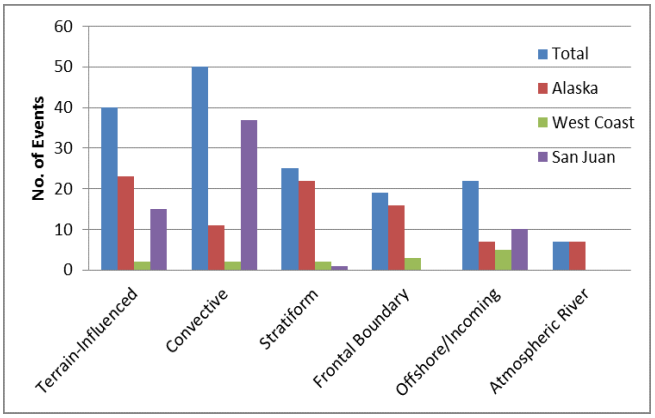


Figure 2. Number of evaluated events by precipitation regime and region. Participants could choose more than one precipitation regime per event.

Table 2. Number of evaluations submitted from each region, and the number of unique forecasters who participated.

Region	Surveys Taken	Participants
Alaska	21	12
West Coast	9	5
San Juan	42	5
Total	**72**	**22**

occurred during their two-month evaluation, totaling 42 surveys among five different forecasters. Analysis of atmospheric river events was confined to Alaska. Forecasters from the three participating forecast offices in Alaska and the APRFC contributed 21 surveys and several additional comments among 12 forecasters at the WFOs and the APRFC. Forecasters assessed events at their own discretion and submitted feedback voluntarily throughout the assessment period as their office staffing and forecaster availability allowed, meaning that it is unlikely that every precipitation event could be evaluated; however, the 70+ feedback forms received tell a convincing story about the utility of LPW in operations. The majority of the participants indicated that they successfully used basic training made available by SPoRT and product developers in order to gain confidence in the application of the product, and relatively few forecasters made further inquiries or comments regarding training throughout the assessment period. Forecasters also reported that the product dataflow was "timely," or that the product's temporal resolution and latency were appropriate for operational use. To demonstrate typical use cases of the CIRA LPW product, forecasters provided examples to the assessment team, and a subset of those are examined in the next section.

3. Analysis and discussion

Participating forecasters provided feedback for a number of individual events, and it is helpful to examine cases that represent typical uses of LPW by forecasters during this assessment. In the cases described below, each event is representative of results regarding the impact of LPW on the forecasting process, the value of LPW over standard TPW products available in AWIPS, and forecaster confidence in information provided by the LPW product. Standard TPW products that forecasters use operationally include model precipitable water, sounder data, and blended TPW—a product that uses the *GOES* sounder, Special Sensor Microwave Imager, and polar orbiting microwave instrument to observe precipitable water globally (Kidder and Jones 2007; Forsythe et al. 2012).

Many of the assessed events in the West Coast were offshore events, observed using satellite data with forecasts guided by operational model output. One of the ways LPW was utilized in operations was to verify or adjust the interpretation of model analyses and forecasts. For example, in a precipitation event from 27 March 2013, a forecaster from MFR observed a short-wave trough as it approached the CWA from offshore (Fig. 3 animation). TPW from the Global Forecast System (GFS) showed the approaching plume of moisture reaching values of about 2.5–3.5 cm (about 1.0–1.4 in) as it approached the coast. The GFS TPW estimates also showed that the short wave was weakening as it came closer to shore (see quote below and the Fig. 4 animation). Observational data from the LPW confirmed that the short wave was weakening. Most of the precipitable water was contained in the surface–850-hPa layer, where the LPW showed <2.5 cm (1.0 in) of precipitable water in that layer (Fig. 5 animation). Specifically, an MFR forecaster stated that "This product showed that the shortwave had limited deep moisture, and that the mid-level moisture was trending lower as the shortwave moved toward the coast. All this helped confirm the idea that the approaching shortwave was fairly weak and weakening." Overall, forecasters from the West Coast WFOs most-often cited that they used LPW in conjunction with models or other products, and this might explain why they also said LPW had a "small" or "very small" impact on their decision process (Fig. 6)—despite having "medium" to "high" confidence in the LPW product (Fig. 7). West Coast forecasters most often indicated that LPW had "large" or "some" value over standard TPW products (Fig. 8). Over all regions, most

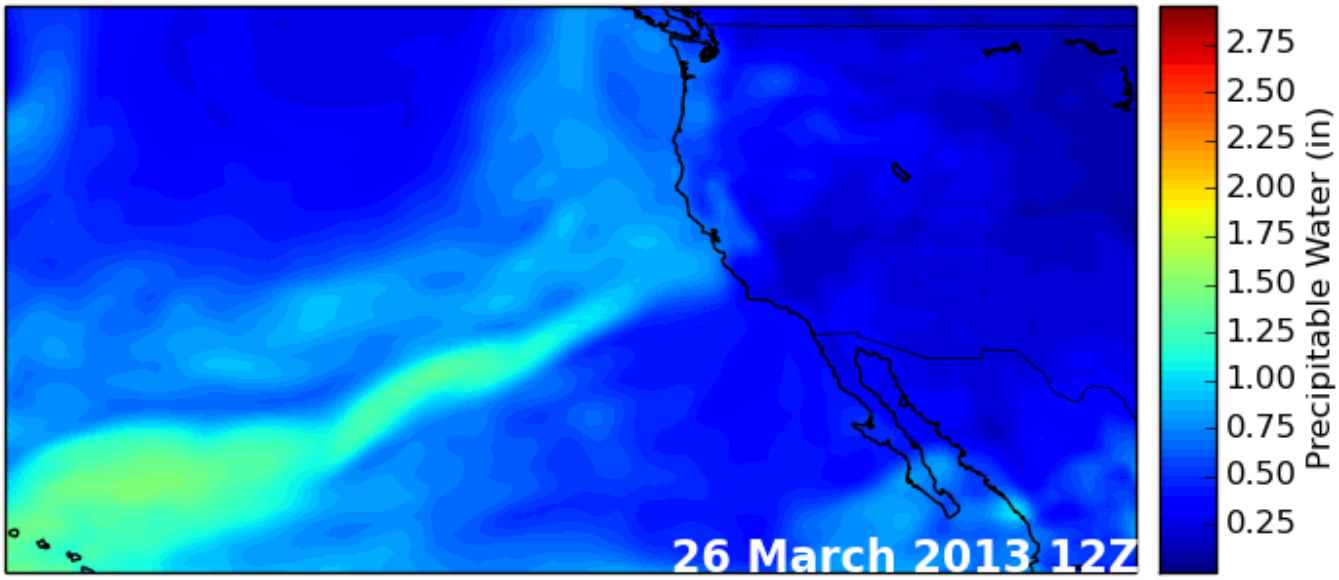


Figure 3. GFS precipitable water (in; multiply by 2.54 for cm) forecast valid 1200 UTC 26 March 2013 showing a synoptic-scale event. *Click image for an animation from 0000 UTC 25 March 2013 to 0000 UTC 27 March 2013*.

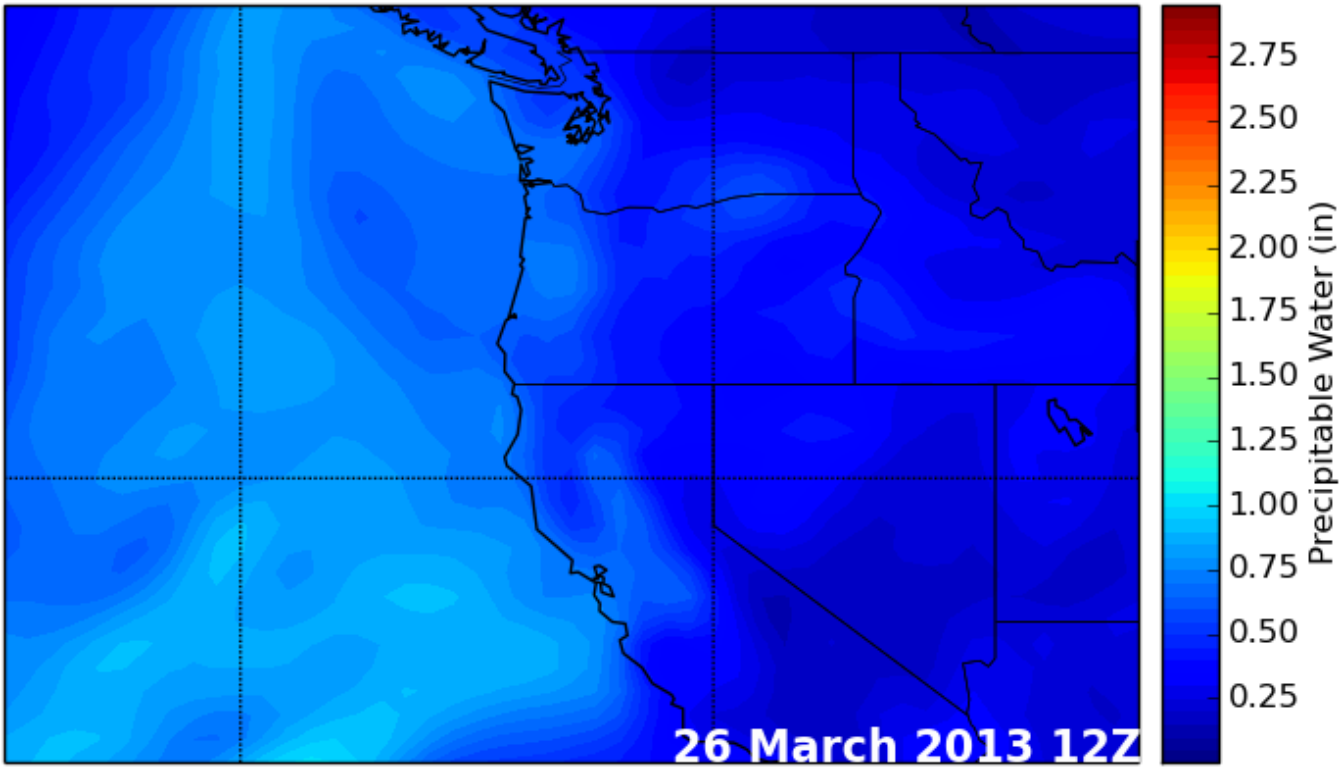


Figure 4. Same as Fig. 3 except scaled appropriately to the relevant WFOs' perspective.

forecasters stated that LPW provided "large" or "very large" value over standard TPW products. Furthermore, almost all forecasters noted that they compared the TPW product made available in the LPW suite to model forecasts of TPW.

Forecasters also found value in using LPW to observe the depth of moisture for diagnosing convective events, often in conjunction with model output or radiosonde data. For example, most of the events assessed by SJU forecasters were convective in nature

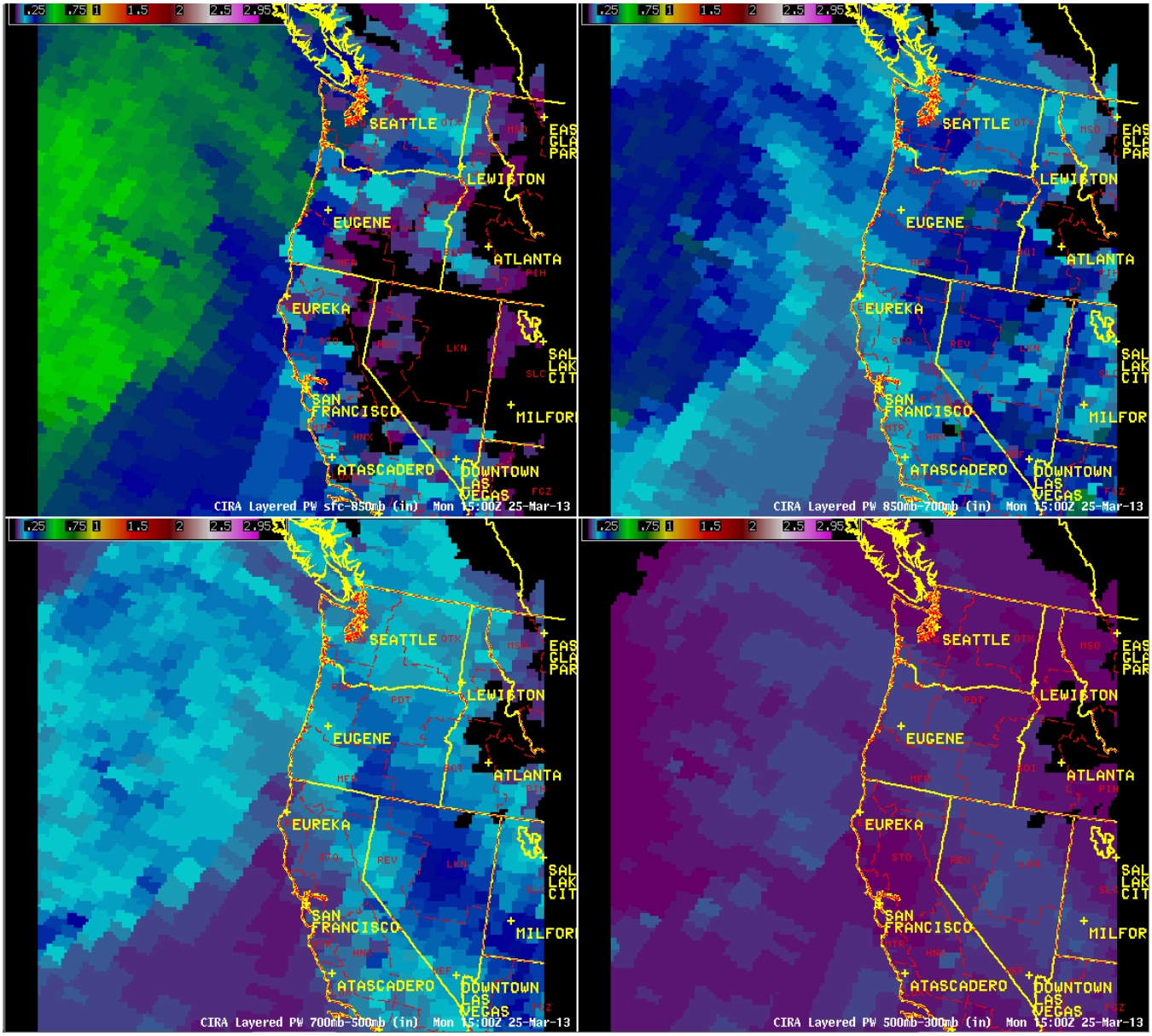


Figure 5. Four-panel display of LPW (in; multiply by 2.54 for cm) showing the decrease in precipitable water associated with the offshore system as it approaches the CWA (static image valid 1500 UTC 25 March 2013). The upper left panel shows the surface–850-hPa layer; the upper right panel shows the 850–700-hPa layer; the lower left panel shows the 700–500-hPa layer; and the lower right panel shows the 500–300-hPa layer. *Click image for an animation from 1500 UTC 25 March 2013 to 0000 UTC 27 March 2013*.

(Fig. 2), and in a case from 28 August 2013, forecasters were examining the potential for convective suppression by the Saharan Air Layer. The 1200 UTC 28 August 2013 sounding at San Juan showed a deep layer of dry air between about 650 and 300 hPa (Fig. 9a). The next available sounding, from 0000 UTC 29 August, showed that the 650–300-hPa layer had become drier (Fig. 9b). LPW observations from 0000 UTC 28 August showed that the dry air had reached the 700–500-hPa layer, and by 0600 UTC the dry layer had begun to reach the surface layer, reducing the observed TPW from nearly 2.5 cm (1.0 in) to <1.2 cm (about 0.5 in) over the island (Fig. 10 animation). By 1800 UTC, the island and the surrounding marine zones showed little TPW throughout the column. A forecaster stated that for this event, "LPW did a great job capturing the dry air at all levels over [Puerto Rico]." For this and other events in which SJU forecasters were using LPW to identify the depth of moisture over the island, forecasters stated that LPW had a "large" or "very large" impact on their forecast process, that they had "high" confidence in LPW values,

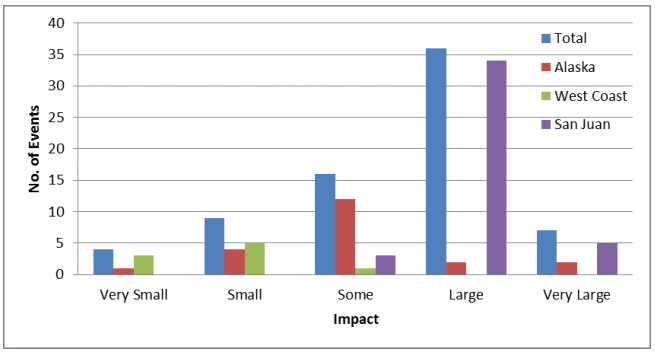


Figure 6. The impact LPW had on forecasters' decision process by region for each event evaluated.

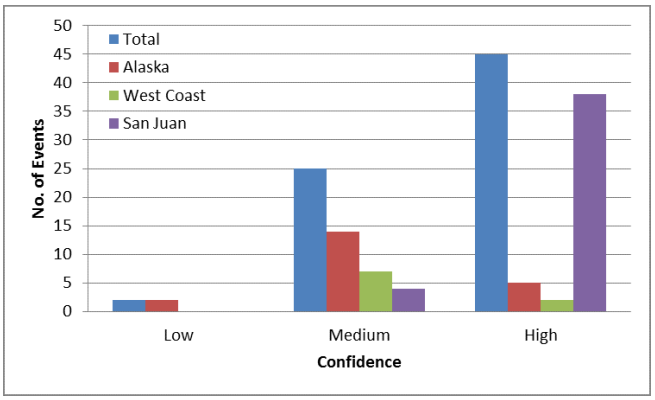


Figure 7. Forecasters' confidence in LPW by region for each event evaluated.

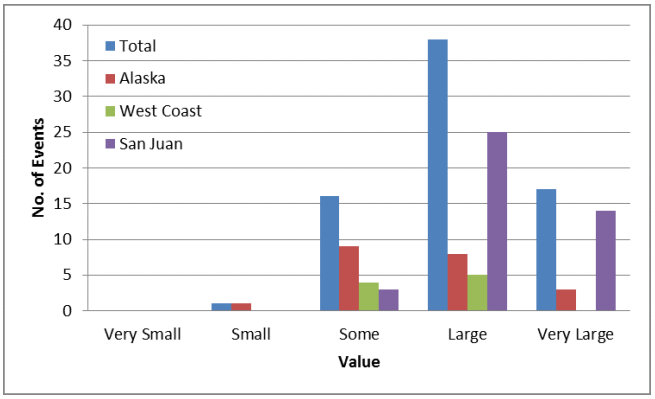


Figure 8. The value of LPW compared to standard TPW, as evaluated by forecasters, for each event observed, categorized by region.

and that the product provided "very large" value over standard TPW products for these events. Forecasters in SJU were complimentary of LPW, and suggested the product be modified to show the Saharan Air Layer in a dedicated layer from 850 to 500 hPa.

Using LPW to determine the depth of moisture also was valuable during high-impact precipitation events, such as an atmospheric river that impacted the Alaska CWAs. There were two atmospheric river events in Alaska during the assessment and a total of seven surveys were completed to describe the use of LPW to evaluate them. Generally, forecasters from the Alaskan WFOs and APRFC found LPW to have "some" impact on their forecast process, but for this multi-day event, Alaska forecasters stated that LPW had a "large" or "very large" impact on their forecast process, that they had "high" confidence in the product, and that the product provided "large" or "very large" value over standard TPW products. Figure 11 shows an animation of an AWIPS four-panel display of four layers, surface–850 hPa, 850–700 hPa, 700–500 hPa, and 500–300 hPa, for 0000 UTC 3 September 2013 until 0000 UTC 8 September 2013. Forecasters for this atmospheric river event used LPW to determine the depth of the moisture plume and whether the moisture was distributed throughout the height of the column or concentrated lower with respect to locations of orographic lifting. The relative intensity of the atmospheric river in the 500–300-hPa layer was helpful for one forecaster from the Juneau WFO who stated that the product "partly influenced" that forecaster's issuance of a flood watch and mentioned the CIRA LPW in an area forecast discussion:

> "The main concern through the rest of the short range is the front that is over the central and eastern [Gulf of Alaska] at the moment. It will continue to move east through the next 24 hours with the rain eventually making it to the rest of the northern panhandle overnight and becoming heavier tomorrow. The rain with this feature remains the main concern as it has a well-developed tropical connection visible on both satellite images and precipitable water retrievals. The plume is also very deep in the atmosphere as very high values of PW are noted up to the 300 to 500 [hPa] layer in the layered PW products. Expected QPF [quantitative precipitation forecast] amounts around 3/4 of an inch in 6 hours around Yakutat this evening and around a half an inch in 6 hours in some areas of the northern panhandle tomorrow."

Another forecaster from AJK later wrote, "The layered PW product was very useful in identifying the AR [atmospheric river] moving up along the front over the gulf [Gulf of Alaska] and issuing an RVS [river flood stage forecast statement] for river rises. Most of the moisture was in the lower levels and this would be the area of high orographic lifting." Forecasters from AJK later stated that the LPW helped them issue flood

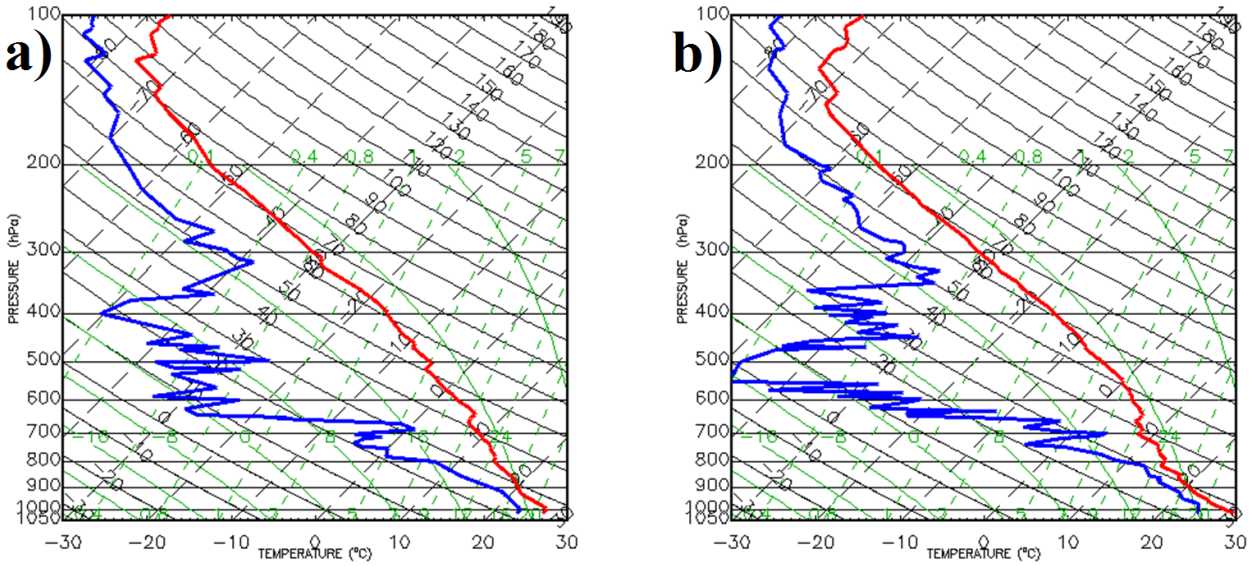


Figure 9. Soundings from San Juan, Puerto Rico, from (a) 1200 UTC 28 August 2013, showing dry air in the 650–300 hPa layer, and (b) 0000 UTC 29 August 2013, showing increasingly drier air in that layer.

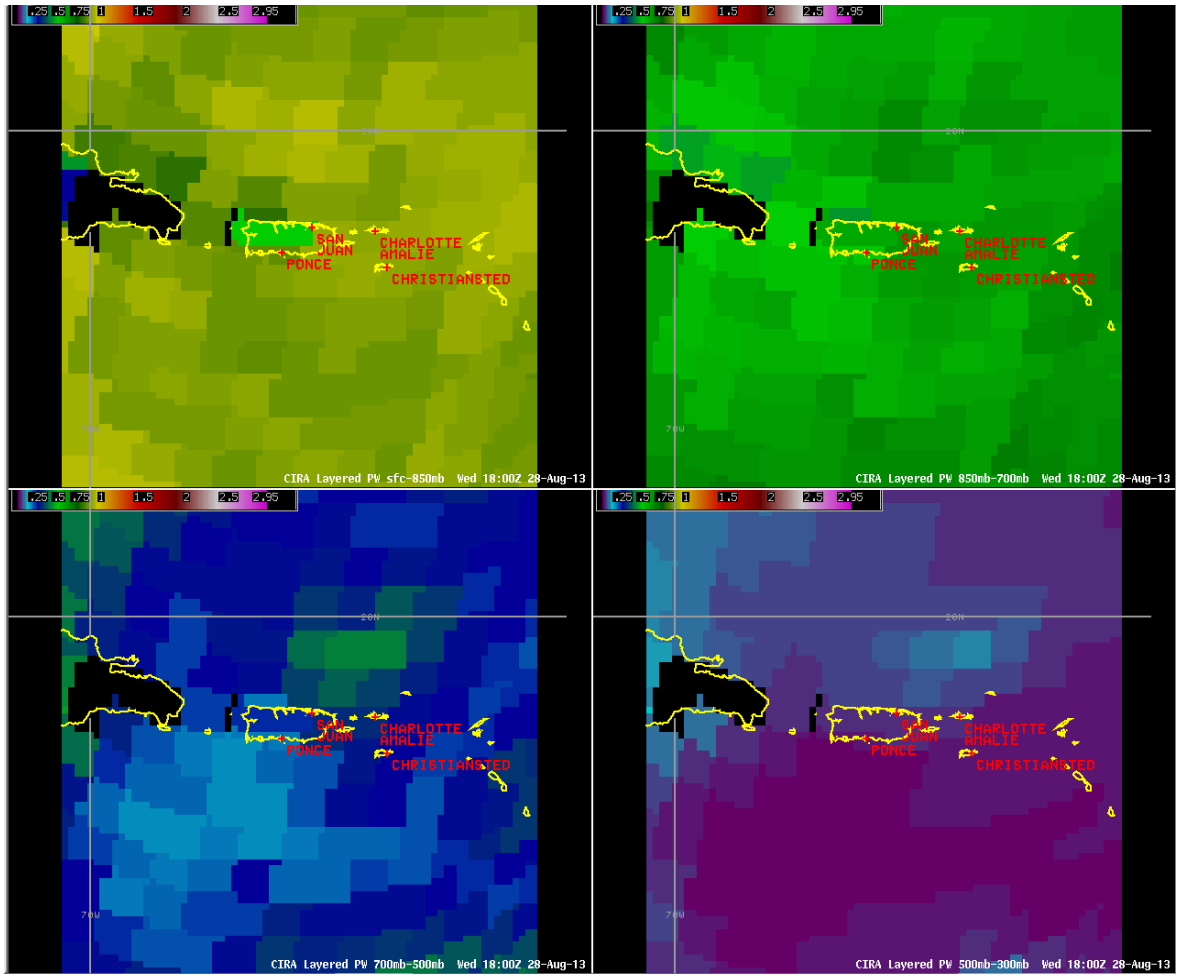


Figure 10. Four-panel display of LPW (in; multiply by 2.54 for cm) showing dry air throughout the column valid 1800 UTC 28 August 2013 over Puerto Rico. The panels are the same as in Fig. 5. *Click image for an animation from 0000 UTC 27 August 2013 to 0000 UTC 29 August 2013*.

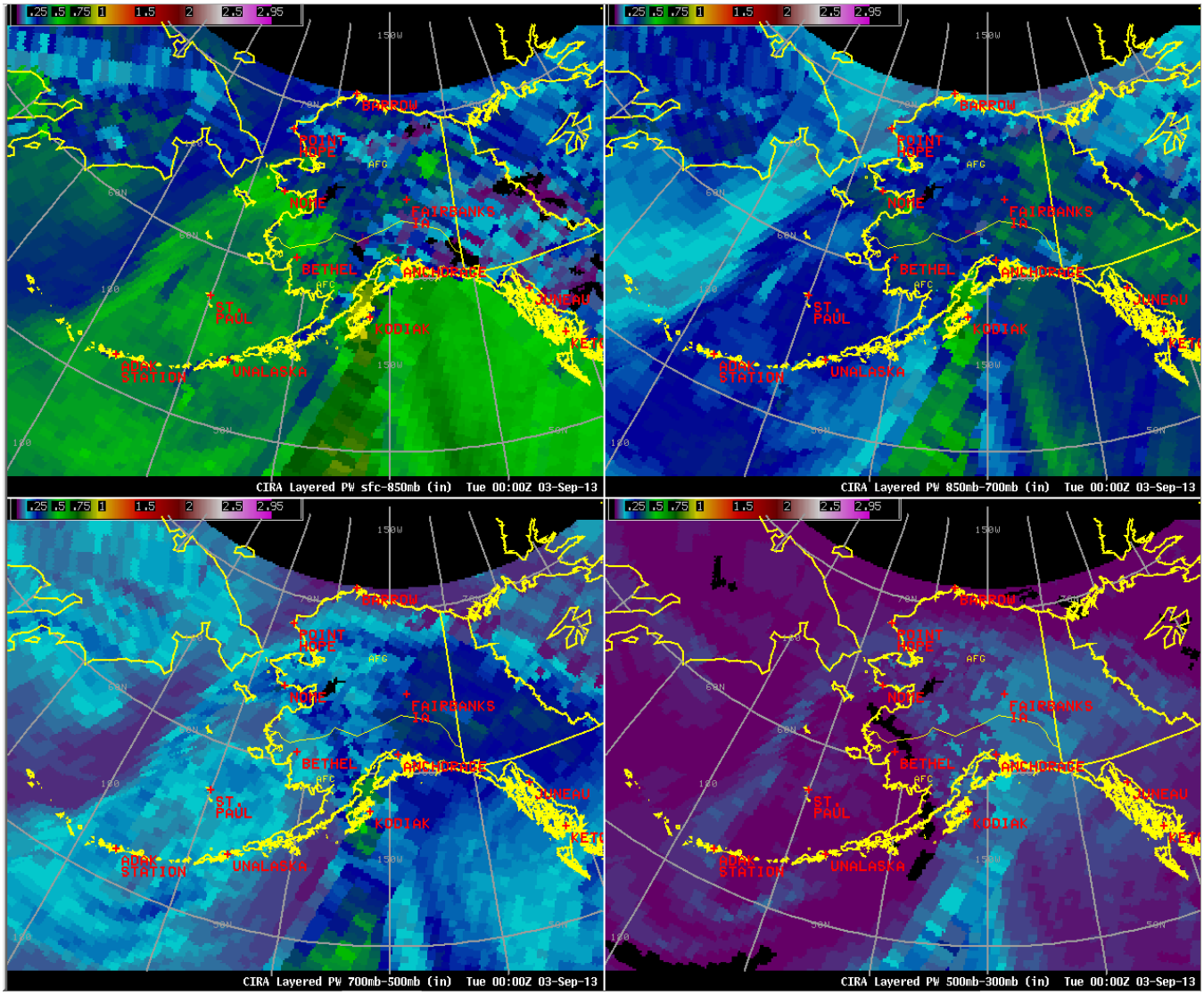


Figure 11. Four-panel display of an atmospheric river event using LPW (in; multiply by 2.54 for cm) valid 0000 UTC 3 September 2013 over Alaska. The panels are the same as in Fig. 5. *Click image for an animation from 0000 UTC 3 September 2013 to 0000 UTC 8 September 2013*.

watches and advisories during the atmospheric river. During this event, some forecasters compared the actual rainfall totals from gauges to the available TPW given by the product and typically found the values to be very similar. An Anchorage forecaster also suggested that it would be "extremely useful" to see LPW expressed as a percent of normal precipitable water for comparison, which product developers would like to incorporate into future versions of the product. Figure 12 shows an animation of the model-derived TPW from the GFS for this event, a frequently used tool by forecasters in determining flood potential during high-impact events.

The aforementioned cases typify the use of LPW in operations by forecasters, including integrating the LPW within their established framework of products. In each case, forecasters reported that the LPW provided additional information to improve forecasting of precipitation in their uniquely challenging forecast environments.

4. Conclusions

In this paper, we described an assessment of the utility of the CIRA LPW product by forecasters on the West Coast of the United States, in Alaska, and in San Juan, Puerto Rico. This assessment represented one

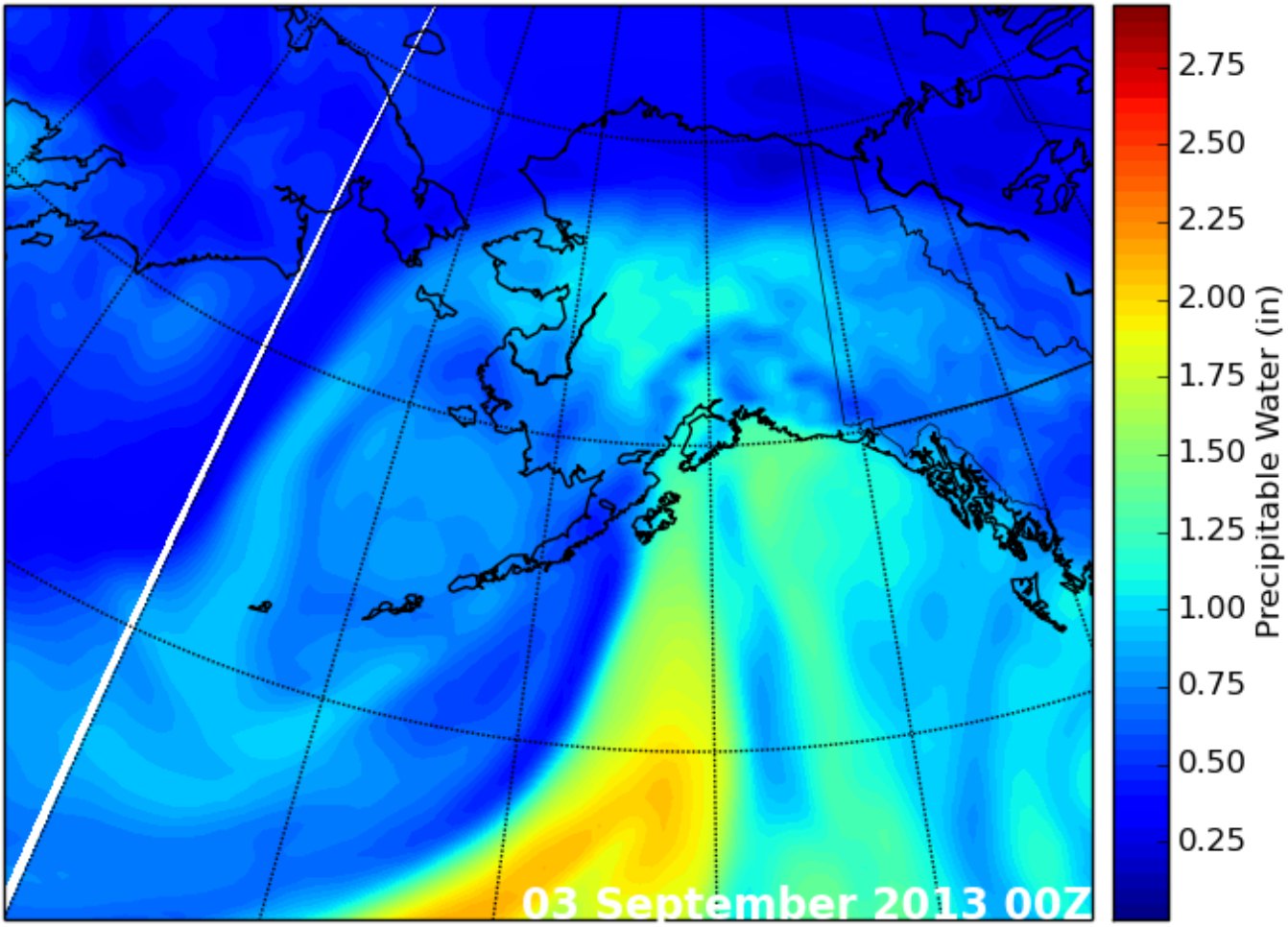


Figure 12. GFS precipitable water (in; multiply by 2.54 for cm) valid 0000 UTC 3 September 2013 from the atmospheric river event shown in Fig. 11. *Click image for an animation from 0000 UTC 3 September 2013 to 0000 UTC 8 September 2013.*

component of a broader, successful transition-to-operations process for the development and use of new, experimental products through delivery of training, integration of the product into the forecaster decision support system, and close collaborations to acquire feedback to assess product impacts and guide future improvements. The assessment of the LPW product confirmed its value within the operational forecasting environment to participants in diverse regions, and across a variety of precipitation modes and environments. Of 72 total assessments, most found the LPW to have "large," "very large," or "some" value over standard TPW products, with San Juan forecasters heavily weighting the results to "very large." Cumulatively, half of the forecasters found that LPW had a "large" impact on their forecasting process, while another quarter stated that it had "some" impact. For all events in which forecasters examined the use of LPW, about 63% had "high" confidence in the product and another 35% had "medium" confidence in the product. Forecaster feedback during this assessment provided opportunities for improvements and development of additional products. Specifically, forecasters in San Juan stated they would find benefit from a layer of precipitable water between 850 and 500 hPa to examine the Saharan Air Layer. Alaska forecasters suggested the raw LPW values could be accompanied by a percent anomaly product similar to what is available for CIRA's blended TPW product that forecasters had already become familiar with. Given the diverse environments in which the LPW product demonstrated value, the product could be applied to similar forecasting challenges throughout the operational weather forecasting community.

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