17.7 THE OROGRAPHIC RAIN INDEX (ORI) PRODUCT AT CIRA

Dan Bikos*, Edward Szoke, Stanley Kidder, Steven Miller and Hiro Gosden

Cooperative Institute for Research in the Atmosphere, Colorado State University, Fort Collins, Colorado

1. Introduction

The Cooperative Institute for Research in the Atmosphere (CIRA) Orographic Rain Index (ORI) product is a short-term forecasting tool that predicts where land-falling moisture plumes will interact with strong terrain gradients in the form of an index. ORI is the product of moisture and terrain-induced “lift”. The moisture data comes from the CIRA blended Total Precipitable Water (bTPW) product (Kidder and Jones, 2007) and the terrain information comes from the USGS GTOPO30 elevation data, therefore the product is 1 km horizontal resolution. Wind data currently comes from the GFS model. ORI is designed to indicate to forecasters where there is short-term (0-3 hr) potential for heavy orographic rain. Increasing values of ORI (up to the set threshold of 250) represent an increasing probability of orographic enhancement (if precipitation is occurring).

This paper will discuss background motivation for the product, followed by product description and cases that illustrate strengths and weaknesses. Product validation efforts will be addressed in section 5. Section 6 will address future improvements to the product based on validation and user feedback.

2. Background

A major forecasting problem along the U.S. west coast is rainfall produced by midlatitude cyclones that is coupled to atmospheric rivers, or plumes of tropical moisture that impinge on coastal mountain ranges (Ralph et al. 2004, 2005, 2006). When such a moisture-rich low-level atmospheric flow undergoes forced ascent and is coupled with the dynamics of the storm, heavy rainfall and flooding can result. This paper describes a new satellite/model-fusion application geared toward assisting forecasters with short-term (nowcast) prediction of terrain-enhanced rainfall. The Orographic Rain Index is based on the simple premise that tropospheric moisture advected into strong topography gradients will induce forced ascent that, when coupled with a favorable stability environment and storm dynamics, can result in an increase in precipitation.

The methodology of Nieman et al. (2002, 2009) is based on Integrated Water Vapor flux from observations at specific sites with GPS satellite for moisture and a wind profiler for wind data. The ORI product utilizes a similar approach, except it covers a domain and uses a blend of observational data and model output. Moisture data comes from the bTPW product (indicated by TPW) and wind data is the GFS 850 mb wind (indicated by V)

$$\mathrm{ORI} = \mathrm{TPW} * V \bullet \nabla H$$

Also, rather than utilizing the slope between fixed sites, the slope is computed across the domain by making use of USGS 30 second (~1 km) resolution elevation data (H).

3. Product description

The ORI product does not predict precipitation amounts; it is *not* a QPF product. Rather, ORI is an index (units of mm m s^{-1}) that represents the amount of moisture advected over sloping terrain. During situations where the contribution

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* Corresponding author address: Dan Bikos, 1375 Campus Delivery, Foothills Campus, Colorado State University, Fort Collins, CO 80523; e-mail: Dan.Bikos@colostate.edu

of orographically enhanced rainfall is largely related to the upslope moisture flux, the ORI will correspond to rainfall rate. It's important to note that ORI is very simple, it does not account for "large scale" contribution to precipitation (i.e., synoptic scale forcing, convection, etc.) or precipitation efficiency. The ORI product is an instantaneous field, with a forecast valid 3 hours from the current time. It can be used by forecasters in the nowcast to very short-term forecast period. One of the unique aspects of the ORI product is the frequent updating of the moisture field via the bTPW product. The bTPW product utilizes a variety of polar oribiting satellites (NOAA, DMSP, Metop-A) which have microwave instruments that allow for retrievals even in cloudy conditions. This is particularly important for Atmospheric River events. As each new polar orbiting satellite pass becomes available, it is included in the ORI product since the product is available on a 3 hourly basis. GOES sounder and GPS satellites also contribute to the bTPW product. The GPS data is useful over land (even in cloudy conditions).

The following thresholds are based on the data shown in Fig. 4 of Nieman et al. (2009). On the high end, they found that almost all rainfall rates of 10 mm h^{-1} or more (which approximately matches the 12 mm h^{-1} criteria used by local forecasters for guidance in issuing flood statements) were associated with bulk upslope IWV flux of 25 cm m s^{-1} or greater. Rainfall rates of approximately 1 mm h^{-1} or less were observed with bulk upslope IWV flux values of approximately 5 cm m s^{-1} or less. The ORI product was calibrated to these thresholds; the upper limit is fixed at 250 mm m s^{-1} to correspond to the Nieman et al. (2009) upper threshold for potential heavy rainfall rates, while values below 50 mm m s^{-1} correspond with light rainfall rates as stated above. The lower limit of ORI is zero (downslope values are set to zero rather than having negative values).

4. Case study

An Atmospheric River impacted coastal California between 28 November to 3 December 2012 (see Fig. 1 for the location of the Atmospheric River on the morning of December 2). Total precipitable water values along the California coast were around 30 mm (greater than 200% above normal). The maximum reported storm total rainfall amount was 52 cm at Honeydew, CA. This type of event was characterized by significant orographic enhancement to precipitation since a relatively moist air mass was being advected by strong low-level winds into the coastal mountain ranges of California. Next, we will demonstrate the utility of the ORI product for this event. The results are generally applicable to precipitation events with a significant contribution by orographic enhancement.

Knowledge of topography is critical for any precipitation event that may experience orographic enhancement. The topography for the region of interest in northwest California is shown in Fig. 2. The key areas here are the coastal mountain ranges where the elevation rises abruptly. Low-level winds with a westerly component would yield upslope flow. Fig. 3 shows the ORI product and KBHX 0.5° tilt radar reflectivity at 0900 UTC 2 December 2012. Higher values of ORI are indicated by warmer colors in this color table. The ORI data is at 1 km resolution, since it is tied to the resolution of the USGS terrain dataset. The radar reflectivity indicates a large area of precipitation, however we do see a few areas that experience beam blockage. ORI may add value to regions that experience radar beam blockage as well as other areas where terrain may make the radar data unreliable.

The greatest utility of ORI comes from a time series such as that shown in Fig. 4. The location of the time series is indicated by the "+" in figures 2 and 3. At this point a precipitation site and river gauge site are located within 5 km of each other. The ORI values shown in Fig. 4 are the maximum values within 15 km of the precipitation site (elevation of 323 m). There is a correspondence between the trend in ORI and precipitation. The forecaster can look for periods when ORI is trending upwards as these may correspond to significant orographic enhancement to precipitation. The hydrologist can also make use of the ORI product by looking for trends in ORI, which in this case also corresponds to changes in river stage height (after a lag time that corresponds to the time of rise).

5. Validation

To determine if the example shown in Section 4 can be extended more generally, here we present a validation of ORI for seven West Coast events. The 7 cases were selected where an atmospheric river could clearly be seen in the bTPW field impacting coastal California. For validation of the ORI product, precipitation and river stage height data were utilized. Case selection was restricted back to October 2009 since the ORI product was developed near that time. First, the precipitation data was chosen at 37 sites in the coastal mountain ranges of California (Fig. 5). For each case, a time period was chosen to capture the entire rainfall event using radar and precipitation data to determine the extent of the rainfall episode. A time series of ORI versus precipitation was constructed at each site for each event at 3 hour intervals to match available ORI data for a total of 170 time series consisting of 5349 data points. A scatter plot of both maximum and mean ORI within 15 km of the precipitation site versus 3-h averaged hourly precipitation rate are shown in Fig. 6. Both maximum and mean plots have a correlation coefficient of 0.54, suggesting that either the maximum or mean value can be used for analysis. One advantage to the mean values is the absence of an upper limit, while the maximum value is set to 250. Focusing on Fig 6a, maximum ORI values less than 50 tend to be associated with light rainfall rates (less than 5 mm h^{-1} for all but one observation). This result is consistent with Fig. 4 from Nieman et al. (2009). Similarly, 3-h average hourly rainfall rates greater than 15 mm h^{-1} were associated with ORI values greater than 100 for all but one observation. The regression line shows some correlation between increasing ORI values and increasing rainfall rates, however there is a large spread in rainfall rates associated with larger (i.e., > 100) ORI values. The interpretation of these results suggests that a higher ORI value at a given time does not necessarily mean a higher rainfall rate, rather a greater probability of a higher rainfall rate. Next, we will assess the utility of the time trend in ORI, to determine if it offers better guidance than simply a specific value at a given time.

Since the ORI product is a 3 hour forecast valid at a given time, and the precipitation values used are 3 hour average rainfall rates over that time period, there is the possibility of time lag offset when comparing the ORI and precipitation data for the purpose of computing correlations. For this reason, we compute lagged correlations 3 hours before, 3 hours after and at the given time. The maximum correlation coefficient was at the given time 54% of the time, 3 hours after 37% of the time and only 9% of the time 3 hours before. This is encouraging in that the majority of the time the maximum correlation was found to be either at the given time or after it so that the ORI trend was leading the precipitation trend, illustrating the usefulness as a short-term forecast product. The maximum correlation for each time series is shown in Fig. 7. In 72% of the time series, the correlation coefficient was greater than 0.5, and in 50% of the cases it was greater than 0.6. The average correlation coefficient for all of the data is 0.58. This is encouraging given the simplicity of the ORI product, the question of how representative a precipitation site is considering it is typically located at a lower elevation than the surrounding terrain and also the inherent uncertainty of utilizing forecast GFS 850 hPa winds.

Validation with river stage height data at 3 hour intervals to match the ORI data follows in a similar methodology to the precipitation data. The motivation for analyzing river stage height data is that orographic enhanced precipitation is poorly measured by point observations of precipitation gauges that are very rarely located on the top of mountains / hills, but instead usually located in a valley. River gauge height data represents runoff from precipitation (and other factors) collected in the vicinity of the river gauge (referred to as the drainage basin). This is an ideal representation of orographically enhanced rainfall in that it represents an areal average (as opposed to a point observation from the precipitation sites) of the precipitation runoff from the surrounding hills / mountains that eventually runs down into the river and is measured as an increase in stage height. The primary limitation of using river stage height is that we assume it changes only as a function of channel precipitation, in reality it is more complicated since it is also a function of overland flow, subsurface stormflow, baseflow and storage components. Another limitation is the time between when precipitation falls and the response as an increase in stage height, this is referred to as the time of rise. The time of rise varies (minutes to days) for each observing site, therefore lagged correlations are computed and the maximum value after the initial time is used (Fig. 8). The sample size for the river stage height data consists of 3923 data points (93 time series) for a subset of the events used in the precipitation data in Fig. 7 near the northwestern California coastline. Compared to the precipitation dataset, the correlations are generally lower. The average correlation coefficient for all of the data is 0.45. The limitations of using river gauge data described above may be circumvented to some extent with a high level of experience of local river hydrology. This experience can lead to anticipation in the time of rise, and perhaps overland flow, subsurface stormflow, baseflow and storage components that influence river stage height.

6. Future improvements

Based on the validation study, two of the main limitations of ORI that led to lower correlation coefficients were 1) the period of orographically induced rainfall over the site and 2) GFS 850 mb wind being unrepresentative of the upslope layer for higher elevation / inland sites. In the case of 1) if the primary portion of the atmospheric river was over the site for an extended period (with strong upslope winds and high moisture), the correlations tended to be higher. For sites where the primary portion of the atmospheric river was further away or passed through for a shorter duration, the correlations tended to be lower. Rainfall may indeed have been heavy at the sites not under the primary influence of the atmospheric river, however the ORI values tended to be lower, resulting in lower correlations. This is tied to the fact that ORI output is not precipitation, rather a product of upslope wind and moisture values. In the case of 2) some of the lower correlation values were due to upslope winds being underdone at inland, higher elevation sites. This can best be represented by example (see Fig. 9). In this case, the station highlighted by “Home” had a correlation of 0.21 for the entire event, however by looking at the GFS 850 mb winds, a tight gradient existed over this site due to the increasing elevation. This time was representative of most of the times for this event with the tight 850 mb wind gradient. Inspection of the GFS 1.5 km Above Ground Level (AGL) winds did not have this tight gradient, therefore this field would likely have been more representative of the upslope winds for this site. The persistence of this tight gradient for a number of the cases (sufficiently inland from the coastline and at higher elevation) suggests an improvement for ORI to utilize model wind at some height (or layer) AGL rather than a fixed pressure level.

Future improvements to ORI include using model wind at some level (or layer) above ground level rather than a fixed pressure level, given the elevation issues noted in the above example. Also, using a model such as the HRRR may be better suited for this application than the GFS with its more rapid time updates. One of the major discoveries of the validation study is the emphasis on time trends of ORI being more useful than a specific value at a given time. This influences how forecasters should best utilize the ORI product, looking at a plan view time animation or time difference field (Fig. 10) to identify regions that need further analysis, then looking at a time series for the region of interest. Additional displays of time series of ORI will be developed to best suite this type of analysis.

7. Summary

By design, ORI is a fusion of satellite and model data and is presented in the form of a forecaster decision aid index to help forecasters locate areas of potential flash flooding caused by atmospheric rivers. It is communicated in the form of an index, as opposed to a rain rate or rainfall accumulation parameter, emphasizing the point that ORI is not a quantitative precipitation forecast (QPF). Rather, the utility of ORI is in its ability to highlight areas of potential concern, when coupled with other sources of information such as knowledge of the location and short term advection of precipitation bands. The ideal usage of ORI would be analyzing a plan view time sequence to identify regions that need further attention, then analyzing time series of ORI at points within the region of interest.

The output of ORI highlights terrain features that are directly responsible for forced ascent. An important user-training element of ORI is guidance on how the product can be leveraged to augment the determination of high-risk areas in short-term flood forecasting. ORI has potential use in monitoring debris flow potential for burn scar regions (i.e., Restrepo et al. 2008)

Few satellite products are communicated in the form of a decision aid. ORI is intended specifically to aid the forecaster in locating areas where flash flooding is possible and where flash flood warnings might be necessary. With only a basic level of training, forecasters will be able to incorporate ORI as a new layer of information within their AWIPS systems. We anticipate that ORI will prove most useful when it is coupled with other information, including cloud cover, radar reflectivity, and various model fields (e.g., stability, vertical motion, potential vorticity, etc.).

References

Kidder, S. Q., and A. S. Jones, 2007: A blended satellite total precipitable water product for operational forecasting. *J. Atmos. Oceanic Technol.*, **24**, 74–81.

Neiman P.J., F.M. Ralph, A.B. White, D.E. Kingsmill, and P.O.G. Persson, 2002: The statistical relationship between upslope flow and rainfall in California's coastal mountains: Observations during CALJET. *Mon. Wea. Rev.*, **130**, 1468–1492.

Neiman P.J., A.B. White, F.M. Ralph, D.J. Gottas, and S.I. Gutman, 2009: A water vapour flux tool for precipitation forecasting. *Water Management*, **162**, 83–94.

Ralph, F. M., P. J. Neiman, and G. A. Wick, 2004: Satellite and CALJET aircraft observations of atmospheric rivers over the eastern North Pacific Ocean during the winter of 1997/98. *Mon. Wea. Rev.,* **132,** 1721–1745.

——, ——, and R. Rotunno, 2005: Dropsonde observations in low-level jets over the northeastern Pacific Ocean from CALJET-1998 and PACJET-2001: Mean vertical-profile and atmospheric-river characteristics. *Mon. Wea. Rev.,* **133,** 889– 910.

——, ——, G. A. Wick, S. I. Gutman, M. D. Dettinger, D. R. Cayan, and A. B. White, 2006: Flooding on California's Russian River: Role of atmospheric rivers. *Geophys. Res. Lett.,* **33,** L13801, doi:10.1029/2006GL026689.

Restrepo, P., Jorgensen, D.P., Cannon, S.H., Costa, J., Laber, J., Major, J., Martner, B., Purpura, J., and K. Werner, 2008: Joint NOAA/NWS/USGS Prototype Debris Flow Warning System for Recently Burned Areas in Southern California. *Bull. Amer. Meteor. Soc.*, **89**(12), 1845-1851.

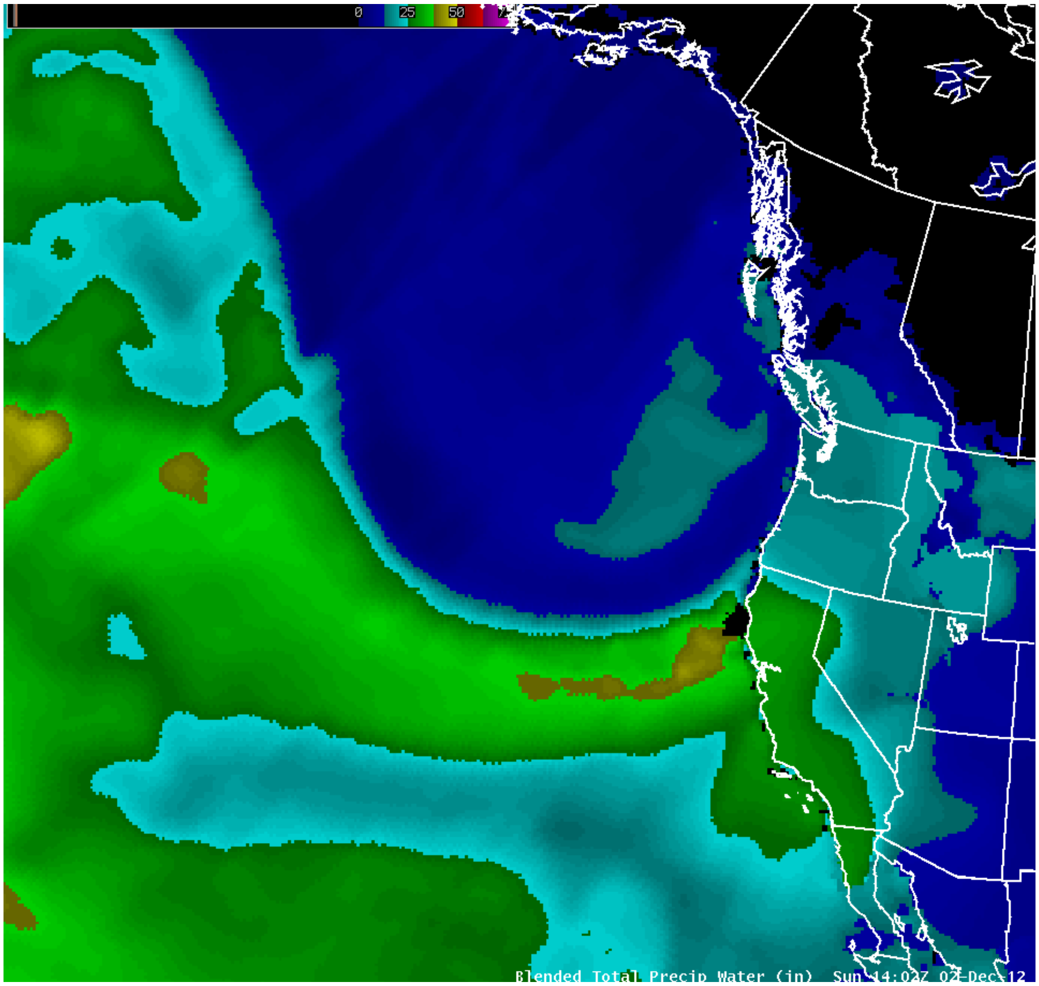

Figure 1. Blended TPW (mm) at 1402 UTC on 2 December 2012. Note the atmospheric river impacting the central and northern California coast. Note the green delineates the 25 mm threshold.

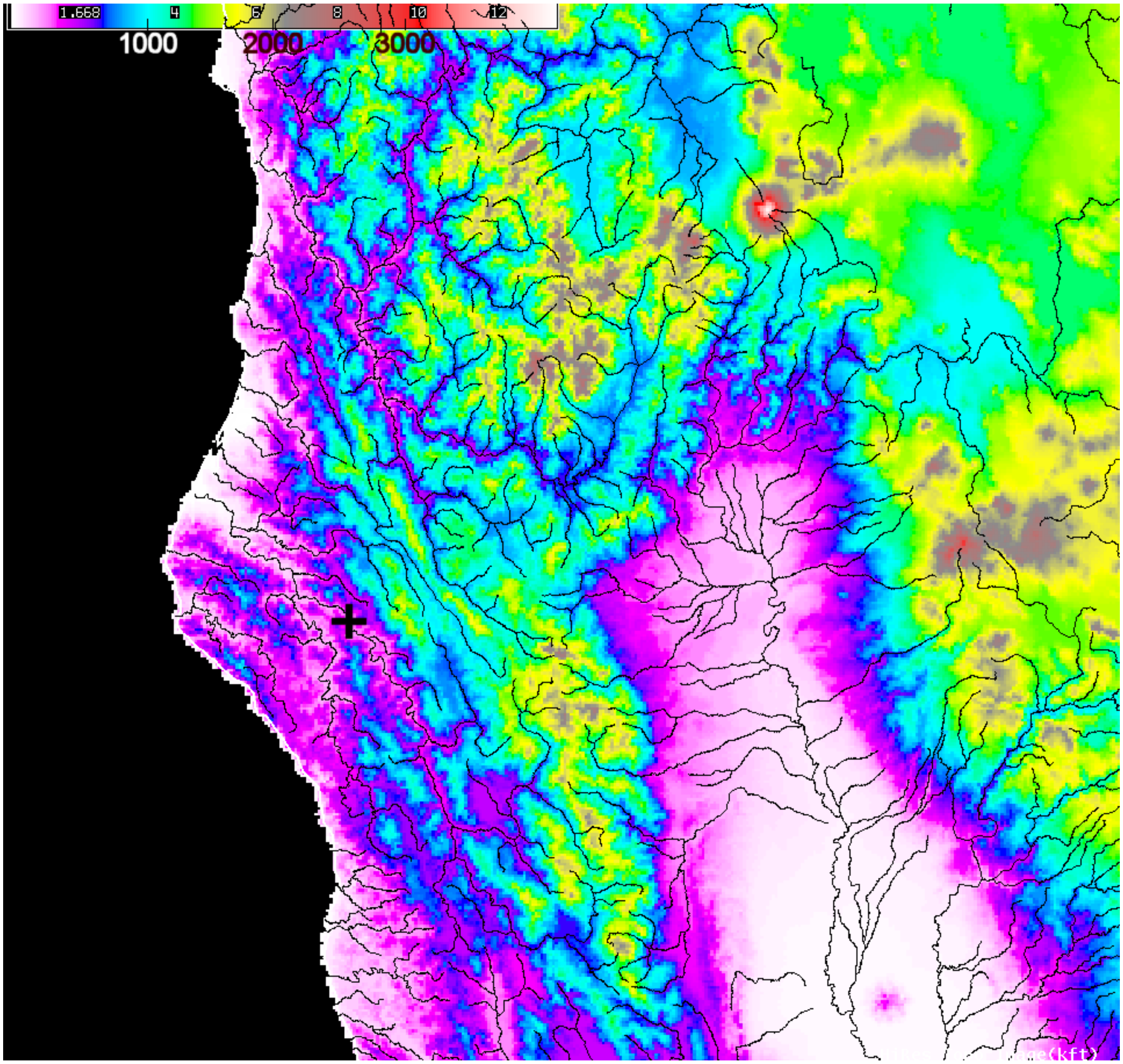

Figure 2. Topographic map with rivers over northwest California. Elevation shaded with scale in upper left, kft (top) and m (below). “+” indicates location of coupled river / precipitation sites shown in Fig. 4.

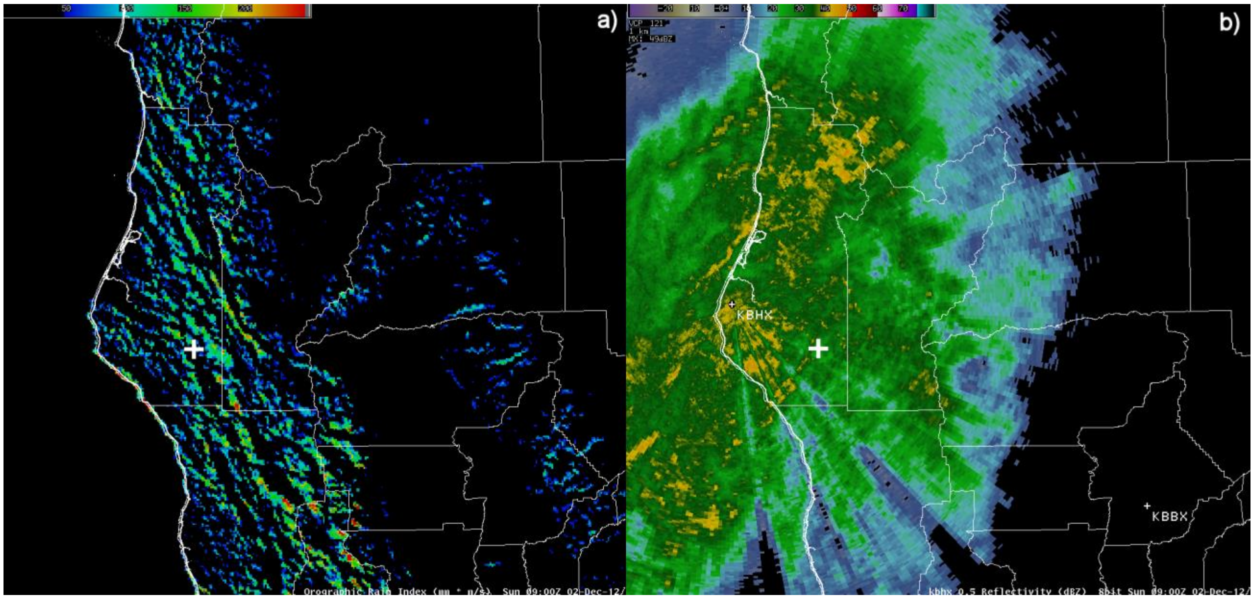

Figure 3. a) ORI product valid 0900 UTC 2 December 2012 over domain indicated in Fig. 2 (above). b) WSR-88D KBHX 0.5° tilt reflectivity at 0900 UTC 2 December 2012. “+” indicates location of coupled river / precipitation sites shown in Fig. 4.

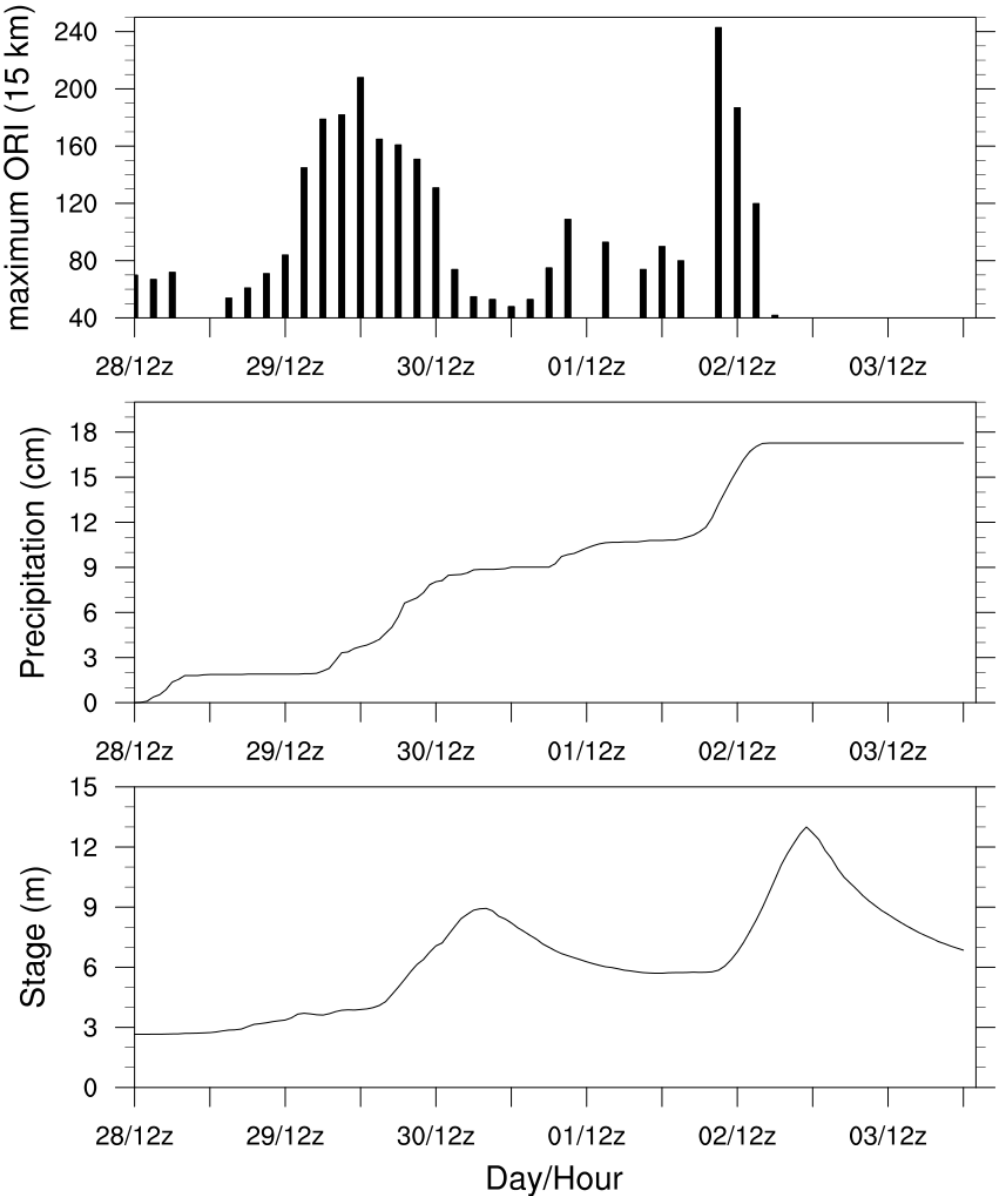

Figure 4. Time series of ORI, accumulated precipitation (cm), and river stage height (m) at the coupled precipitation / river gauge sites indicated by "+" in Fig's 2 and 3 from 1200 UTC 28 November to 0000 UTC 4 December 2012. Distance between the river gauge and precipitation site is 5 km. Elevation at precipitation site is 323 m. ORI values are within 15 km of the precipitation site.

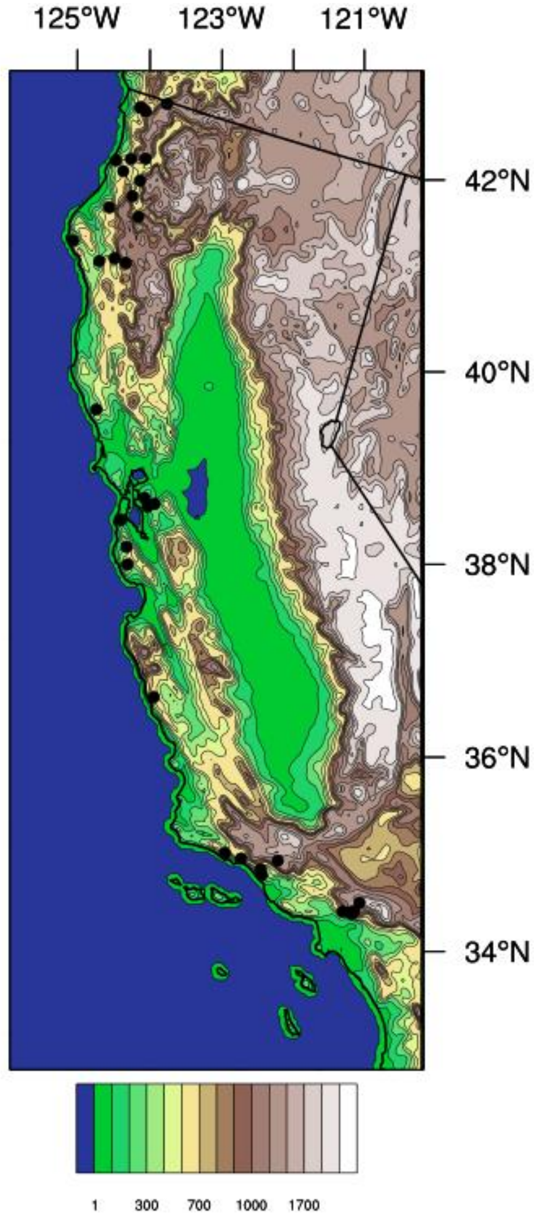

Figure 5. Location of precipitation sites along with elevation (m) over California. Map is on a Lambert-Conformal projection.

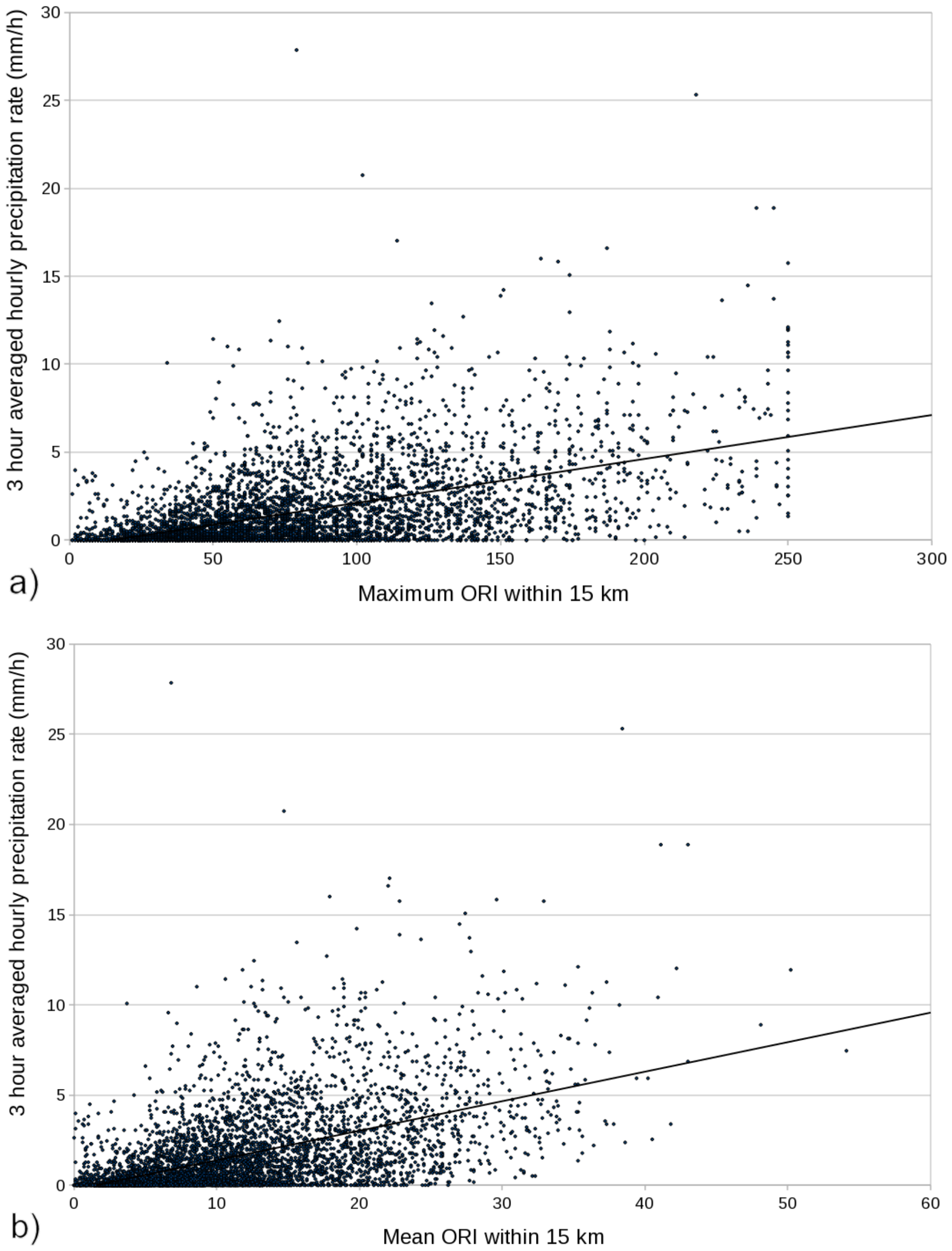

Figure 6. a) Scatter plot of maximum ORI within 15 km of precipitation site versus 3 hour averaged hourly precipitation rate (mm/h). b) as in a) except mean ORI. Both plots have a regression line and a correlation coefficient of 0.54.

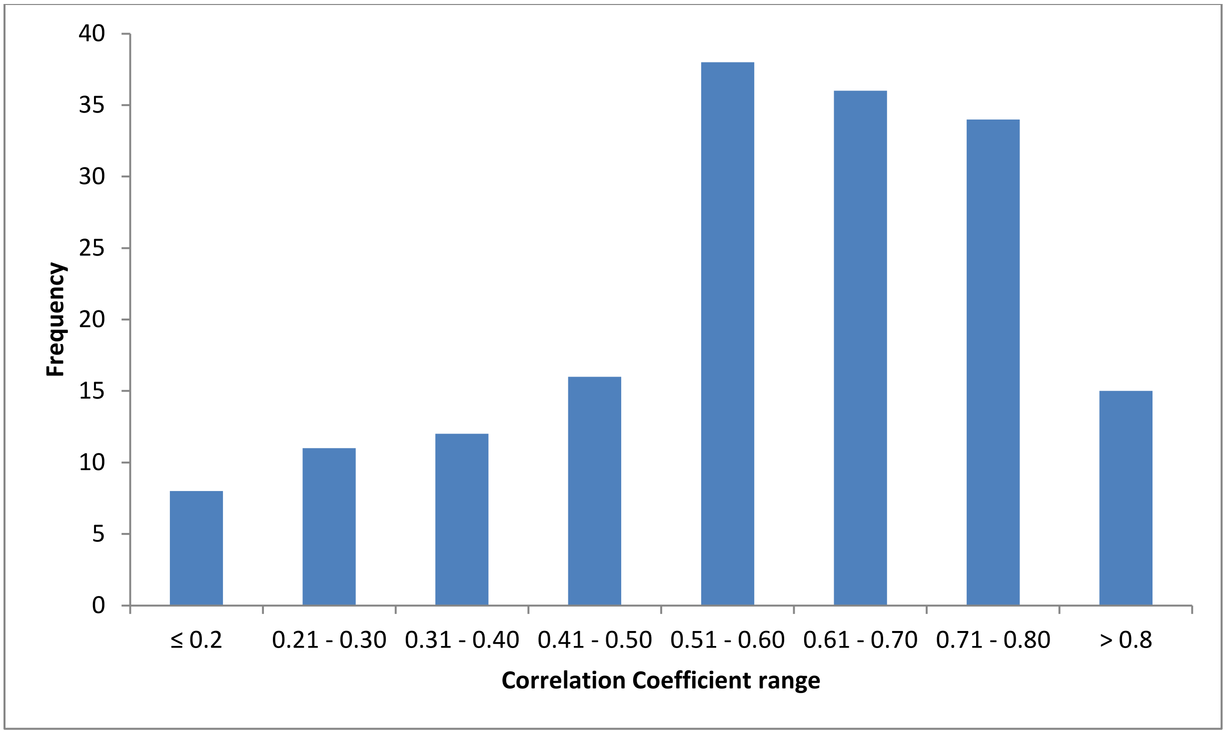

Figure 7. Histogram of Pearson product-moment correlation coefficient for each time series of mean ORI within 15 km versus 3 hour average precipitation rate.

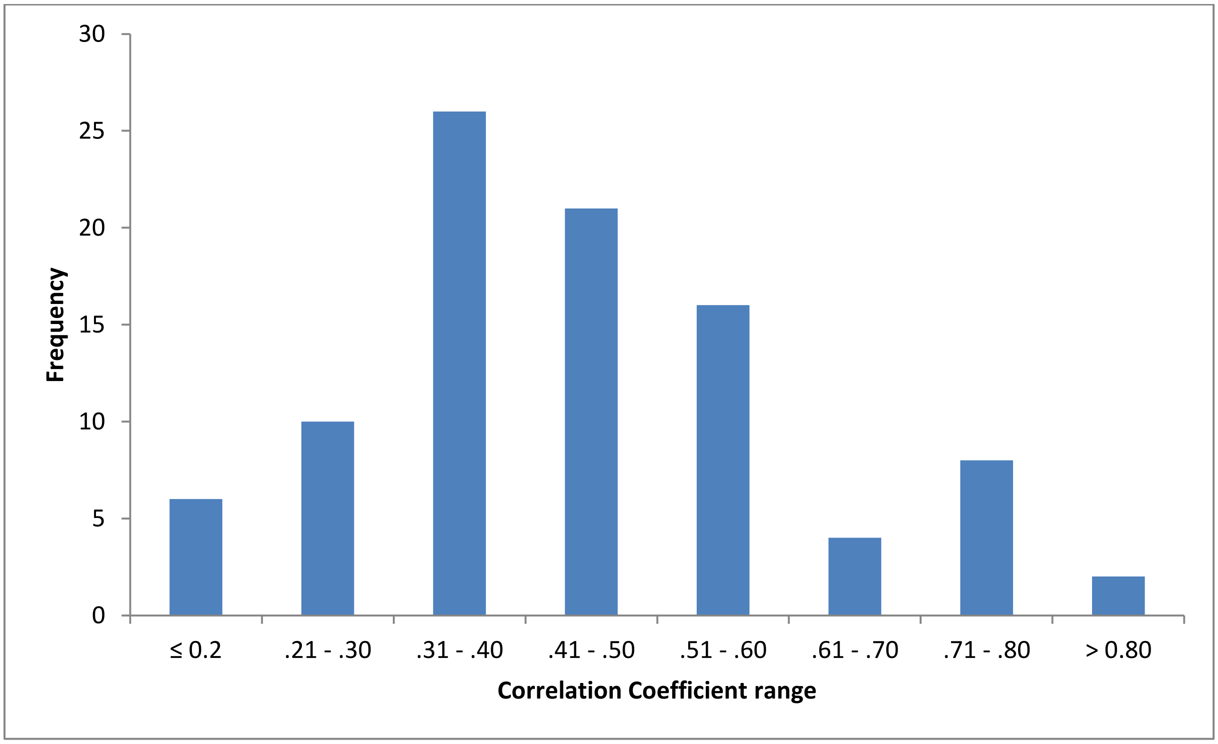

Figure 8. Histogram of Pearson product-moment correlation coefficient for each time series of mean ORI within 15 km versus river stage height.

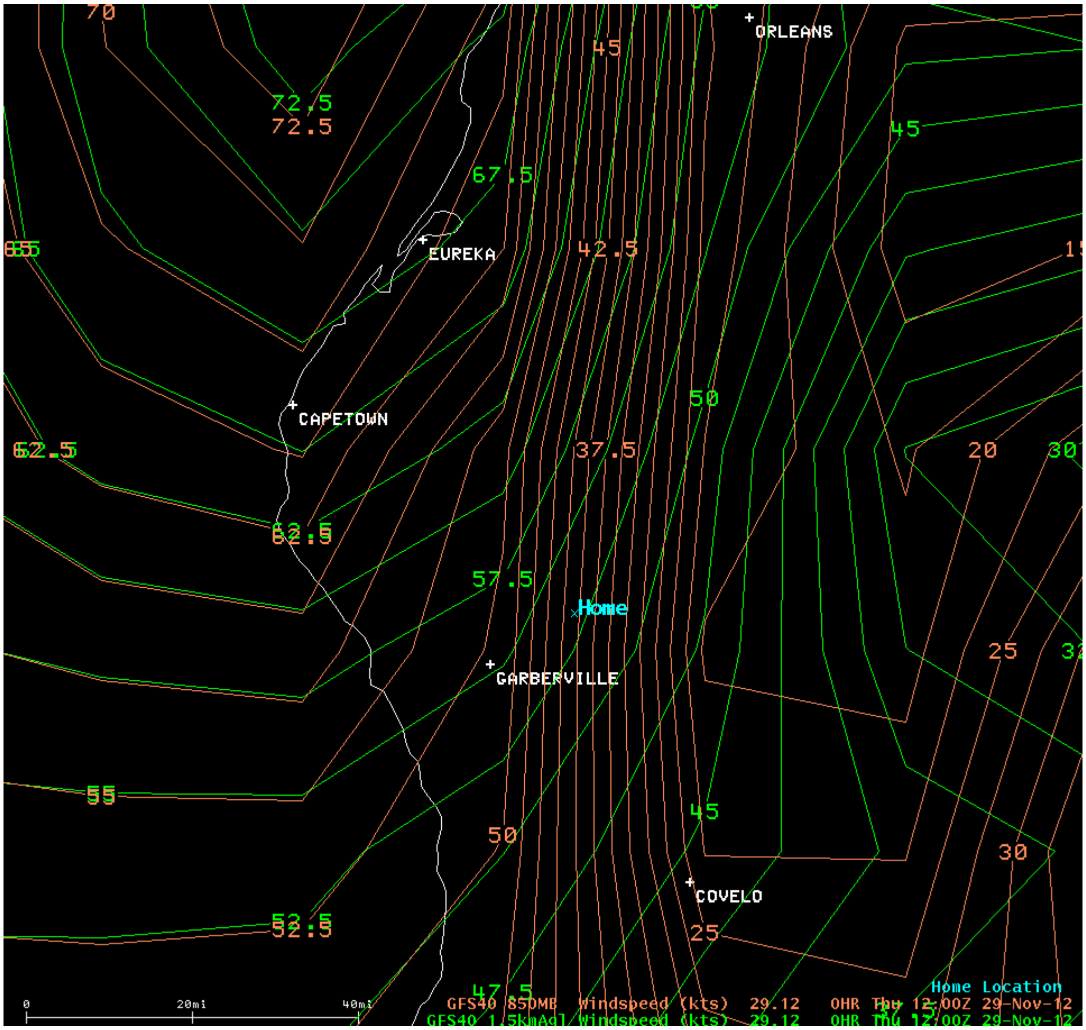

Figure 9. GFS 850 mb wind (green, kts) vs GFS 1.5 km AGL wind (salmon, kts) for 1200 UTC 29 November 2012. Home cursor indicates one of the sites that had a R value of 0.21 for this event.

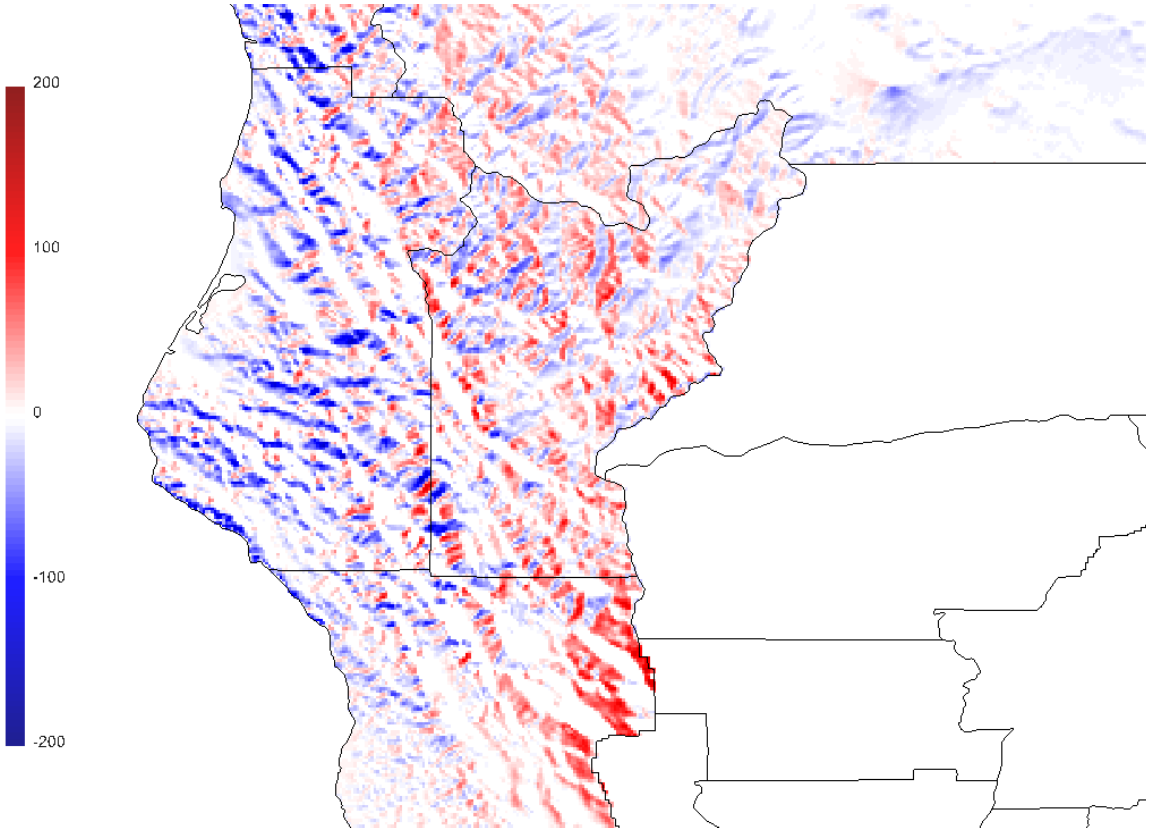

Fig. 10. Difference between ORI product at 1200 UTC and 0600 UTC 2 December 2012 over northwest California, a 6-hr trend display.