2.6 Atmospheric River Forecasting Products for Situational Awareness

2.6.1 Overview

FIRO's success is predicated on the availability of forecasts with sufficient skill at lead times to support a more flexible strategy for water management decisions at Lake Mendocino. This section addresses lead times and emphasizes the importance of a partnership between the entity providing a forecast and the end-user who needs to understand that forecast before acting upon it.

The products described in this section are based on over five years of effort to understand AR prediction and impacts and represent collaborative efforts to address stakeholder information needs. These products have generated new and avid awareness of predictions of AR strength, position, duration and impacts among the water resources management, hazard mitigation, and forecasting communities and decision makers.

This task has produced the following accomplishments:

- Developed the CW3E website (http://cw3e.ucsd.edu) that provides unique observations, analyses, and a comprehensive collection of tools to support forecasting of ARs (section 2.6.2 and 2.6.3).
- Developed a new way of categorizing and communicating the strength and potential impacts of landfalling ARs, the AR Scale (section 2.6.5).
- NWS has incorporated CW3E AR forecasting tools into briefings and frequently uses information on the CW3E forecast website (section 2.6.6).
- Lake Mendocino reservoir operators are using the tools to inform their operations (section 2.6.6).

2.6.2 Deterministic (Control) Forecast Products

CW3E provides forecasts of large-scale meteorological conditions from the Global Forecast System (GFS) and ECMWF Integrated Forecast System (IFS) deterministic runs out to seven-day lead time. These large-scale maps provide a first look at relevant meteorological conditions ahead of precipitation events and can be evaluated by a forecaster to understand a storm's evolution and salient characteristics. This large-scale perspective and forecaster guidance can manifest as official forecast products via analog forecasting approaches, which aid in providing context for impending events. These maps also provide a point of reference for AR diagnostics. The variables available include IVT and IWV, to identify an AR, as well as dynamic and thermodynamic information at multiple atmospheric levels that can be used to infer the meteorological processes that are driving a forecasted storm's precipitation distribution and rates.

Figure 2.6.1 shows an example of a 72-hour forecast map of integrated vapor transport (IVT) on 14 February 2019 prior to a particularly intense AR that caused the Russian River to exceed monitor stage height at Guerneville. Forecast maps are derived from NOAA NWP predictions of large-scale and small-scale aspects of landfalling ARs up to 7 days in advance. The maps are part of the foundation of CW3E experimental forecast outlooks -- the information is also unique in that national sources of forecast information do not specifically focus on AR diagnostics (e.g. IVT), even though IVT arguably conveys the most important information for western-coast water resource management.

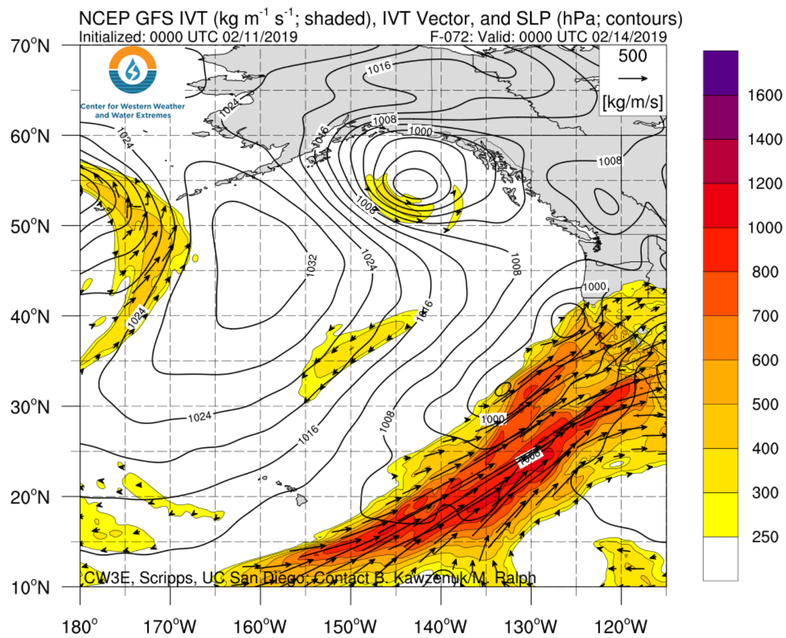

Figure 2.6.1. Global Forecast System (GFS) 72-hour lead time forecast of integrated water vapor transport (color; kg m-1 s-1) and sea-level pressure (contour; hPa) valid on 14 Feb. 2019 at 00 UTC. A strong AR has made landfall over the California coast, and the northern edge of the AR is being sustained over the Russian River watershed by a mesoscale frontal wave, identified by the local low pressure minimum immediately offshore.

In addition to the GFS and ECMWF forecasts, CW3E also produces weather maps from the West-WRF forecasts during the NRT season (Section 2.3.3). West-WRF improves forecasts of AR landfall position compared to GFS and provides the highest spatial resolution for longer lead times than is available for any similar mesoscale NWP models run nationally. The West-WRF forecast products are utilized by several partners including NWS, water agencies and CA Federal-State Flood Operations Center.

Using the deterministic runs of the GFS, CW3E has generated interactive tools to provide guidance on watershed-scale precipitation forecasts. One such tool shows mean areal precipitation across regional HUC-8 watersheds, which can be clicked-on to pull up the 10-day GFS deterministic model precipitation forecast for any given watershed (Figure 2.6.2). The tool's functionality also includes an ability to query NOAA/NWS RFC hydrograph forecast products. Development of these tools was supported by the California Department of Water Resources, and FIRO has supported their maintenance.

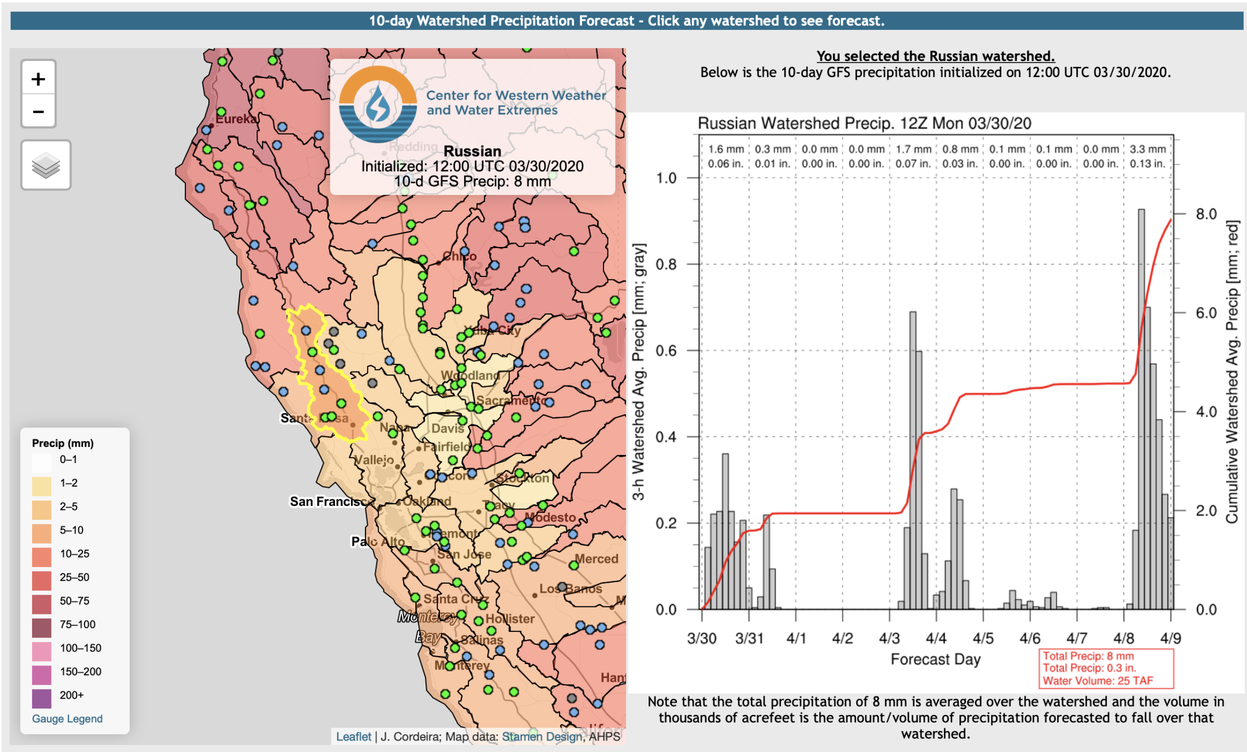

Figure 2.6.2 The shaded polygon layer (left) illustrates the 10-d forecast of precipitation from the NCEP GFS model that is averaged over each "HUC-8" watershed, whereas the color-coded point data circles illustrate observations of the river stage from the NWS River Forecast Center hydrographs (the example image was taken from 3 Mar. 2020). On the CW3E website, these layers are fully interactive – clicking a circle location pulls up its respective analysis/forecast hydrograph in the panel on the right. Clicking on a watershed pulls up 3-hourly precipitation (shown in right panel).

2.6.3 Probabilistic Forecast Products – Uncertainty Information

Synoptic maps of forecast meteorological conditions from a deterministic model provide each NWP system's single best representation on how the atmosphere is expected to behave, but FIRO requires additional information on how certain those predictions are. This is a challenging task given that not all meteorological conditions are equally predictable or equally well-observed, and that not all models perform equally well. A skillful ensemble of forecasts is thus needed to provide actionable information about forecast uncertainties from NWP for decision support in the 21st Century. Currently, CW3E generates its suite of forecast products using both the GFS and IFS ensembles (21 and 51 members, respectively). The ensembles are intended to account for, and illustrate, model uncertainty in initial conditions, sub grid-scale processes, and model physics that lead to forecast error. The differences between the ensemble members provide information about the forecast's certainty, and the performance of the ensemble mean and spread through time define the ensemble's skill. Collectively, these pieces of information can be used for any given forecast scenario to establish confidence in a forecasted outcome.

For example, CW3E uses ensemble forecasts to convey forecast confidence regarding landfalling AR conditions via the AR landfall tool (Figure 2.6.3). The AR Landfall Tool, developed by Dr. Jay Cordeira (Plymouth State University) and Dr. Marty Ralph (CW3E), provides longer-range ensemble forecast guidance of duration and timing of landfalling ARs up to 16 days in advance. Recent upgrades include adding AR orientation, which recent research (e.g. Hecht et al. 2017; section 2.3.4) has highlighted is a necessary parameter for Russian River watershed precipitation potential in most AR events. The landfall tool diagram on 11 Feb. 2019 can be used to infer model agreement (p = 1.0, or all 21 ensemble forecast IVT > 250) in AR landfall at the latitude of Bodega Bay on 13 Feb (3 days later), though the shading at 4 and 5 day lead time indicate considerable ensemble member disagreement in the duration of landfalling AR conditions. This particular event led to rapid changes in the hydrologic forecast for the Russian River, which can be interpreted through a lens of forecaster uncertainty about the duration of AR conditions.

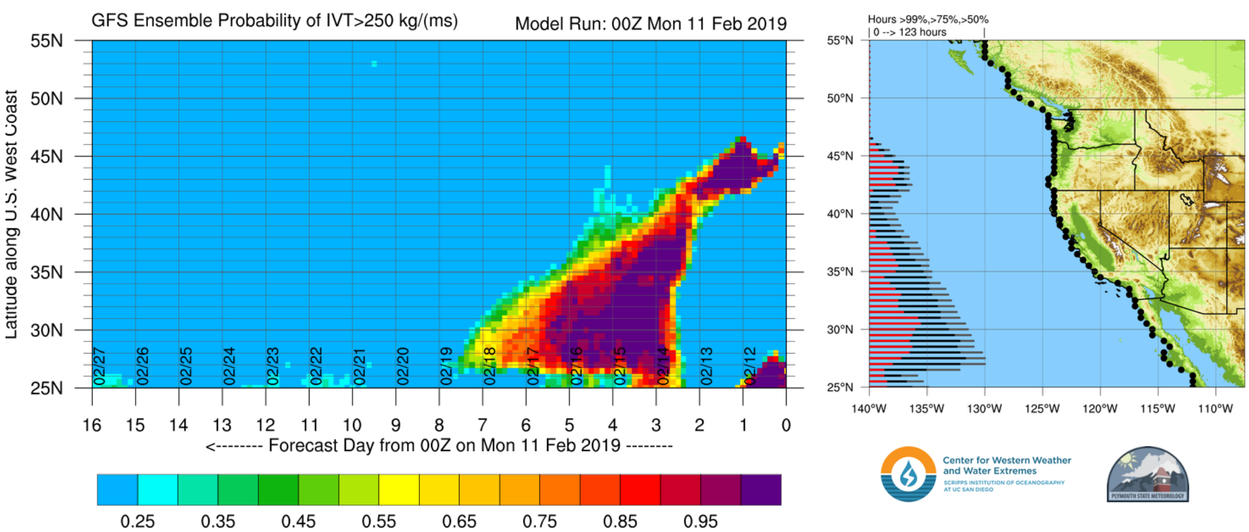

Figure 2.6.3 AR landfall tool taken from the CW3E website on 11 Feb. 2019. The probability of AR conditions at a coastal point through time is displayed as the percentage of ensemble members with IVT > 250 (colorfill) (left). The duration of landfalling conditions according to ensemble probability thresholds of 99%, 75% and 50% is plotted at half-degree latitude increments (right).

The forecasted intensity of AR conditions is also paramount to hydrologic impact prediction. One specific ensemble-based tool to provide improved information on forecasted AR intensity is the "Plume Diagram", which conveys ensemble spread of AR intensities above a given location as a function of lead time. Ongoing decision support tool development includes creating a version of the product that merges GFS and ECMWF ensemble information.

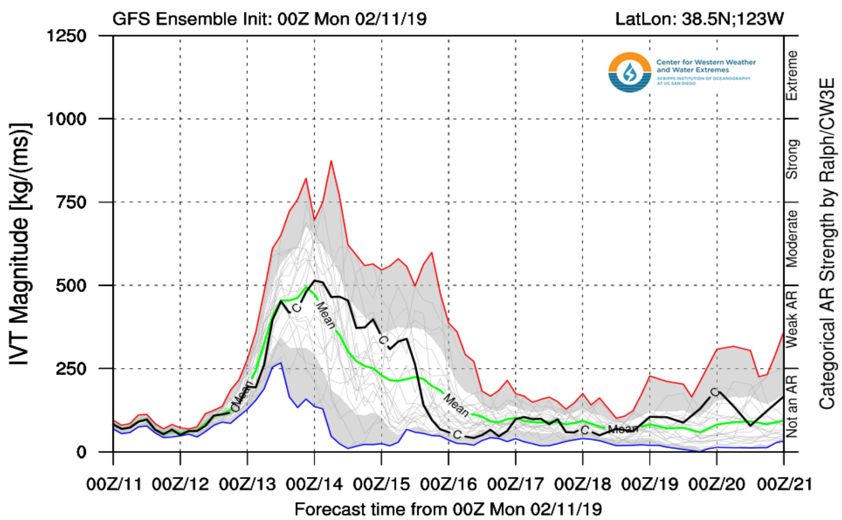

Figure 2.6.4 AR plume diagram taken from the CW3E website on 11 Feb. 2019. The variability of forecasted AR conditions at a coastal landfall point through time is demonstrated by individual traces of IVT magnitude through the forecast period. The maximum and minimum values at any given time are traced by the red and blue lines, respectively. The black line identifies the deterministic "control" member and the green line identifies the ensemble mean.

The above examples represent just a couple of the most frequently used forecast products in briefings issued by CW3E ahead of AR events, and are also the products that receive the most web traffic (including from stakeholder and NWS IP addresses; based upon Google Analytics). A growing collection of other deterministic and probabilistic products are available through the website and, depending on event conditions, can provide essential information to further understand event evolution, predicted impacts, and NWP forecast confidence.

Beginning in 2019, CW3E is partnering with ECMWF to utilize and display AR diagnostics based on their ensemble global modeling system, which is often regarded as the best in the world for many weather applications. The EC ensemble has also demonstrated utility for AR forecasting at one-to-seven day lead times, and bringing it into the mix will provide crucial multi-model uncertainty information for FIRO operations.

2.6.4 Evaluation of Forecasts

A necessary ingredient for turning forecasts into truly usable and especially reliable decision-support products is understanding their performance through time. Specifically, a forecast tool can only be used with confidence if it has previously been established that it skillfully predicts events that occur, and skillfully does not predict events that do not occur. Notably, the skill of forecasts must be assessed by lead time to determine the range of times for which they are reliable for decision support at Lake Mendocino. Figure 2.6.5 provides an example of AR landfall tool performance over the WY 2019 winter season. It can be seen that ensemble agreement varies from event to event, though on average the ensemble system achieves full internal agreement at 3 day lead time and routinely exhibits a high degree of reliability (e.g. 75% of ensembles in agreement of observed landfall) at > 5 day lead time.

Continued development of these products, including their extension to ECMWF data, requires long-term evaluation that then provides context to the information that they provide in future forecasted events.

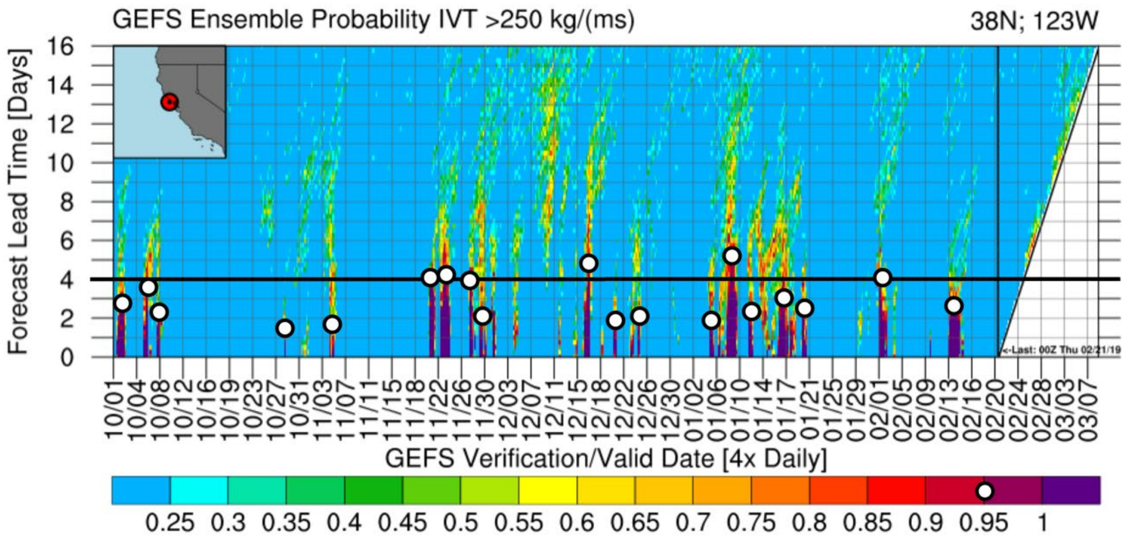

Figure 2.6.5 GEFS probability of IVT magnitude >250 kg m^{-1} s^{-1} as a function of verification date (x axis) and lead time (y axis). Read from top to bottom to gauge lead-time predictability of individual events. The lead time at which 95% of GEFS members were in agreement is marked by a white dot. The black line spanning the width of the image marks the 4-day lead time for reference.

Additionally, several automated and post-season verification tools have been developed that run in parallel with the GFS, EC and West-WRF near-real-time forecasting products. These verification analyses include a measurement of forecast accuracy for AR landfalls, precipitation amounts and spatial extent, and freezing level altitude. The former two analyses are scientifically innovative, in that they apply object detection algorithms to both forecasts and environmental analyses to create estimates of the forecast error (see section 2.3.3 for more detail). In addition to benefiting the development of West-WRF forecast skill, these verification analyses measure the forecast accuracy of daily forecast information throughout the winter season and provide valuable information regarding how forecast errors are trending for a given event.

2.6.5 The AR Scale

Scales for meteorological phenomena, such as hurricanes and tornadoes, have proven very useful for quickly communicating to the public about potentially hazardous conditions, forecasting, and conducting research. ARs are the most impactful storm type in California and along the U.S. West Coast and are a major source of extreme precipitation. At the same time, most ARs do not cause major floods and hazards, so that it is important to communicate which of the forecasted ARs will most likely cause problems and require special operations.

Despite the widely recognized importance of ARs, no concise method has existed for conveying the likelihood of benefits and hazards that communities face during a particular AR event. In response, CW3E and a number of collaborators from academia, NWS, and CA DWR developed a scale for characterizing the strength and impacts of ARs (Figure 2.6.6; Ralph et al. 2019). The intent is for this scale to provide a crucial tool for officials with an operational need to assess flood potential in their jurisdictions before storms strike. Unlike other scales that focus primarily on damage potential, such as the Fujita scale for tornadoes or the Saffir-Simpson scale for hurricanes, the AR scale accounts not only for storms that can prove hazardous, but also for storms that can provide benefits to water supply (Ralph et al. 2019). In the context of FIRO, the AR scale provides a metric that distills forecasts of the key ingredients that drive regional precipitation in the Russian River, and historical information about the benefits and hazards of similar conditions, into a single number that can be used to convey a forecasted storm's potential reservoir filling benefits and watershed flooding hazards.

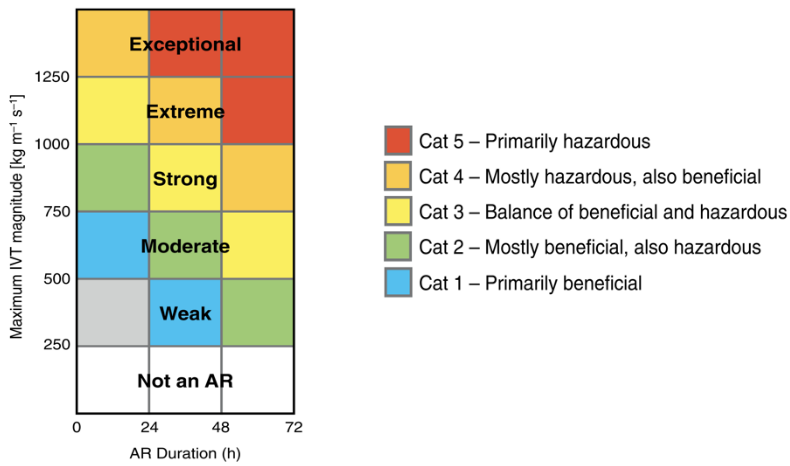

Figure 2.6.6 The AR Scale ranks atmospheric rivers from 1 to 5 and creates the categories "weak," "moderate," "strong," "extreme," and "exceptional" based on the intensity and duration of IVT conditions in a given location. When an AR lasts in an area for less than 24 hours, it is demoted by one category, but if it lingers for more than 48 hours, it is promoted. This approach is based on research showing that a combination of strong water vapor transport with long duration over a location, is what causes the greatest impacts.

2.6.6 Integration and Improvement of Forecast Products

CW3E has developed many tools to make modern forecast products more accessible to a variety of stakeholders and done so in a manner that exemplifies a research and operations partnership. One such example is how CW3E has worked with reservoir managers at Lake Mendocino and the US Army Corps of Engineers to ensure complete understanding of the forecast information and decision support tools that are produced, and has created opportunities for end-user feedback, especially regarding ensemble-based uncertainty products. Previous discussions between CW3E and stakeholders in a similar context have highlighted that information is not translated between atmospheric scientists, hydrologists, reservoir operators and stakeholders with perfect fidelity, and that assuming that it is may have negative consequences. An iterative approach to developing forecast diagnostics and decision support tools that meets end-user needs in a simple and effective manner via constant interaction (e.g. technical workshops and individual meetings between forecasters and operators), is essential to FIRO success. A relevant example of this process occurred after CW3E forecast products were implemented for decision support during a series of strong AR storms that impacted the Russian River in February 2019. Afterwards, the CW3E meteorologist responsible for developing the products met with the USACE reservoir operator who employed the tools to be debriefed on how they had been interpreted and implemented throughout those events, with a focus on future improvements. Interaction between the source of forecast information (CW3E, NWS) and the end-user (USACE, DWR, SWA) will remain essential as ongoing FIRO projects venture to develop enhanced decision support tools that must be readily understood and easily employed.

In addition to direct interactions with reservoir managers, aforementioned online forecast products are also routinely used by the NWS (as demonstrated by many conversations, collaborations, and CW3E website statistics). CW3E forecast products both inform the official operational meteorology and hydrology forecasts and are frequently used in NWS pre-event briefings. CW3E is in a unique position to develop research-based tools that are specific to western needs on regional to individual-watershed scales (e.g. FIRO on the Russian River).

To reach a broader water management community and for use by the media, CW3E synthesizes and publishes discussions of forecasted events via “AR Outlooks” and abridged “AR Quick-Looks” on its website. These products communicate evaluations and summaries by CW3E meteorologists of the full range of available forecast information in advance of impactful precipitation events. They distill that information into readily interpretable bullet points and supporting figures that can aid stakeholder preparation.

2.6.7 Conclusions and Recommendations

As the name implies, the integration of forecast information into reservoir operations is central to FIRO. Because ARs account for approximately 50% of the precipitation in the Russian River (Ralph et al., 2013) and are the cause of major floods in the basin (Ralph et al., 2006), the online forecasts products specific to ARs that CW3E has developed, maintained and refined are a major contribution to providing enhancing forecast information availability and confidence for FIRO. The probabilistic tools are especially beneficial because they provide information about forecast uncertainties. The recent addition of the ECMWF products further enhance this depiction of uncertainties by illustrating model-to-model differences among several excellent forecast NWP systems. The CW3E website aims to integrate a considerable amount of forecast information from various sources into succinct decision support tools that are designed based on reservoir operator and other stakeholder inputs.

The following recommendations will enhance the benefits of FIRO:

- Continued development and refinement of forecast products, including their extension to include ECMWF data.
- Long-term evaluation of forecast products to provide a quantitative basis for confidence (and limits on confidence) in forecasted events.

- Continued engagement with stakeholders, particularly reservoir managers and NWS forecasters, to support the integration of AR forecast information into their operations
- Responding to stakeholder requests for specific tools and information that effectively delivers the state of the science in ways that meet their evolving needs.