The West-wide Evapotranspiration Forecast (WwET4Cast) Network

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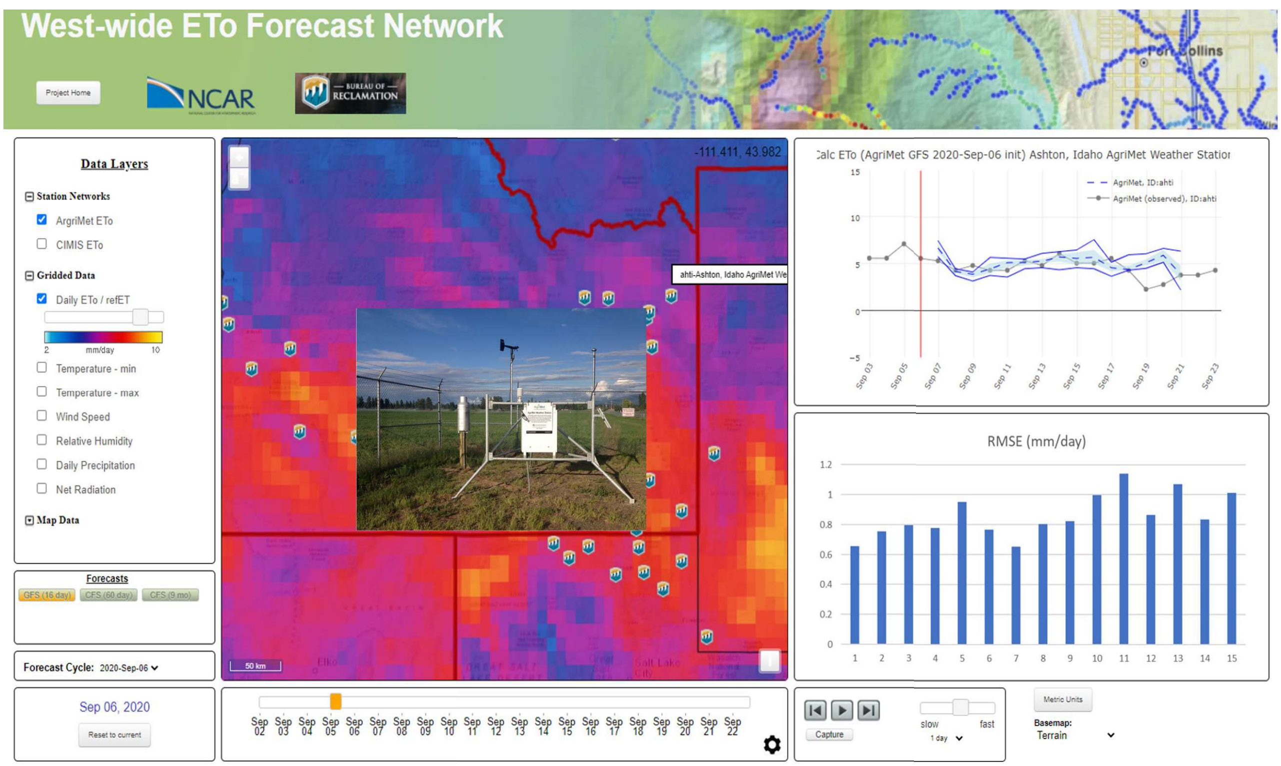

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14. ABSTRACT
This project addresses forecasting of daily reference evapotranspiration (ETo) at agro-meteorological stations based on downscaled meteorological variables from 1) the NOAA Global Forecast System (GFS) model producing 16-day, daily ETo forecasts; and 2) the NOAA Climate Forecast System (CFS) model resulting in seasonal ETo forecast outlooks out 60-days (daily ETo) and 6 months (monthly ETo). The results of the project include the development of the West-wide Evapotranspiration Forecast (WwET4Cast) Network, which is a web-based service for generating and disseminating the forecasts at agro-meteorology stations and grid cells throughout the western United States.

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Forecasting, reference evapotranspiration, web-based platform

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Disclaimer

Acknowledgements

This project was made possible through a long and productive collaboration with colleagues at the US Bureau of Reclamation, especially Dr. Michael Tansey, whom we would particular like to thank for his vision and creative ideas regarding the need to advance our capabilities of forecasting water demand. Traditionally, water supply forecasting has been a focus of the Bureau and this is a first project that advances demand forecasting capabilities- the other half of the water balance challenge. We would also like to thank Dr. Troy Peters of Washington State University, who engaged with us over the project duration to envision how the forecasting products that would come from this project, could be woven into his irrigation scheduling tool. We would also like to thank Ms. Jama Hamel, the AgriMet Program Coordinator, for engaging with us on the vision for adding value to the AgriMet network via sub-seasonal and seasonal forecasting. Funding support for this study, provided by the Reclamation Office of Science and Technology, Research and Development Office managed Dr. Kenneth Nowak, is gratefully acknowledged. We would also like to thank our colleague, Andy Gaydos who worked to code and deploy our vision of the WwETFcst Inspector. We would also like to thank Dr. Andy Wood, who helped us with the operational forecasting system that was deployed on an NCAR server that he originally deployed for forecasting water supply. We would also like to thank Dr. Michael Anderson of the California Department of Water Resources for his time and thoughtful inputs as a project advisor. The responsibility for any errors or omissions remain solely with the authors.

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Acronyms and Abbreviations

A	ACC	Anomaly Correlation Coefficient
	AgriMet	Agriculture Meteorological Network
	API	Application Programming Interface
	ASCE	American Society of Civil Engineers
B	BPA	Bonneville Power Administration
C	CAWWG	Climate Change and Water Working Group
	CIMIS	California Irrigation Management Information System
	cfs	cubic feet per second
	CFS	Climate Forecast System Model
	oC	Degrees Celsius
D	DWR	California Department of Water Resources
E	ETo	Reference evapotranspiration
	ETa	Actual Evapotranspiration
	ENSO	El Nino Southern Oscillation
G	GCM	Global Climate Model
	GFS	Global Forecast System Model
K	Kc	Crop Coefficient
L	LAI	Leaf Area Index
M	MJO	Madden Julian Oscillation
N	NCAR	National Center for Atmospheric Research
	NOAA	National Oceanic and Atmospheric Administration
O	OWDI	Open Water Data Initiative
R	RUE	radiation use efficiency
	RMSE	Root mean square error
	RAL	Research Applications Laboratory
	Rn	Net solar radiation
S	S2S	Sub-seasonal to Seasonal
T	TC	Tropical Cyclones
U	USBR	United States Bureau of Reclamation also the Bureau
	VOD	Vapor pressure deficit
V	VPD	Vapor Pressure Deficit

Measurements

°F	degree Fahrenheit
c	centimeter
µg/L	micrograms per liter

Contents

Tables

Figures

Executive Summary

The 2013 Climate Change and Water Working Group (CAWWG)[1] identified needs for both short-term monitoring and forecast products with lead times ranging from hours to years to improve water-resource decision making. The answers sought for decision making in water-resource management are "when and how much water to use," particularly for irrigated agriculture. Accurate and timely applications of water to the field can lead to improved crop yields while saving water, time, and money. Recognizing the need to monitor and observe weather and climate conditions across the west to improve water management, the USBR (Reclamation, hereafter), in collaboration with the Bonneville Power Administration (BPA), partnered in 1983 to form a Cooperative Agriculture Weather Network. The network is a series of automated data-collection platforms that provide meteorological and other data for supporting the near-real-time management of Reclamation's water operations in the Pacific Northwest. Reclamation then established a dedicated network that focused on agricultural needs, dedicated to crop-water use modeling and other agricultural applications, such as the weather data needed to model evapotranspiration. This system is referred to as the AgriMet network. While knowing what the weather *has* been like over the past few days or weeks is certainly useful for agricultural growers and water-resource managers, arguably of greater use to these decision makers is "*what will the weather be in the future?"* Noting that users of AgriMet data rely on the station-based observations for information, the primary aim of this project was to add value to AgriMet and other meteorological networks by creating forecasts of the same meteorological fields that are observed at the site and used to estimate crop evapotranspiration.

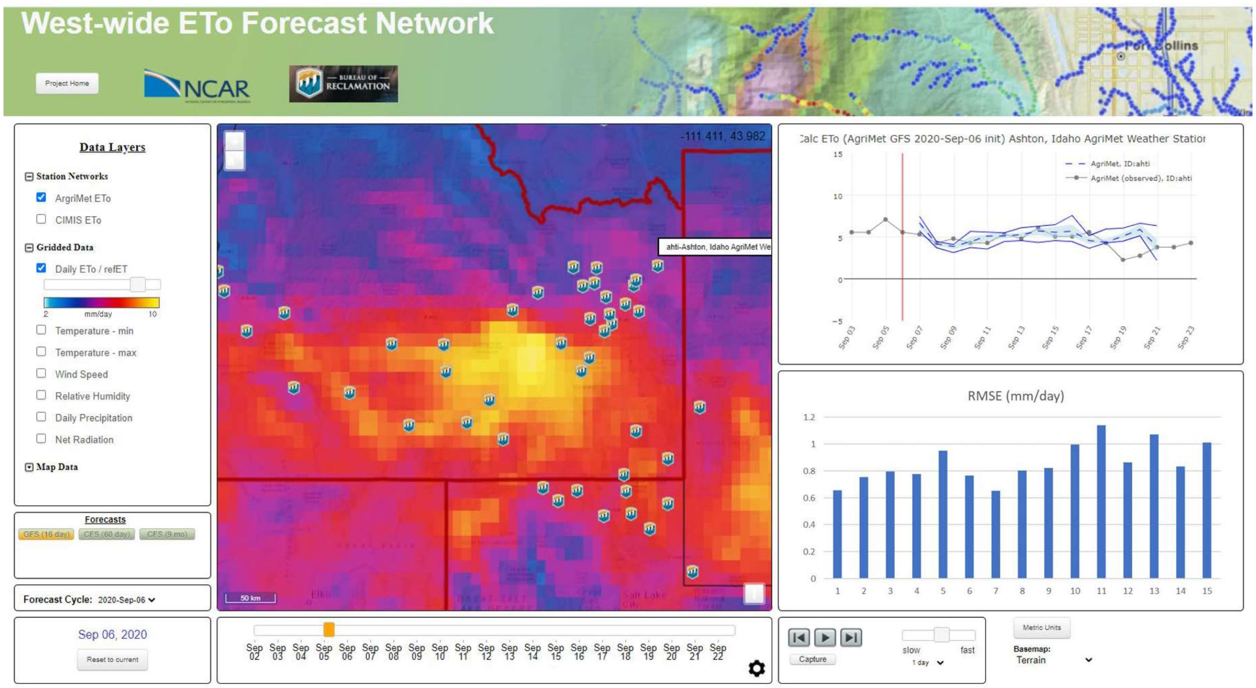
This project addressed both the monitoring of daily reference evapotranspiration (ETo) at agro-meteorological stations and the forecasting of ETo, based on downscaled meteorological variables from 1) the NOAA Global Forecast System (GFS) model producing 16-day, daily ETo forecasts; and 2) the NOAA Climate Forecast System (CFS) model resulting in seasonal ETo forecast outlooks out 60-days (daily ETo) and 6 months (monthly ETo). From the research perspective, the combination of ETo monitoring at the large network of agricultural meteorological stations throughout the western United States with forecasted ETo provides the data necessary to evaluate the reliability, skill, and uncertainty of the ETo products, and serve as guidance in their improvement. This project addressed Open Water Data Initiative (OWDI) goals by leveraging a previously developed ETo agro-meteorology station network and added value to that network with forecasted ETo at various forecast lengths.

The results of the project include the development of the West-wide Evapotranspiration Forecast (WwET4Cast) Network, which is a web-based service for generating and disseminating the forecasts. Figure ES1 shows the web-browser-based graphical user interface and the spatial pattern of ETo for a particular summer day in southeastern Idaho, with the marks on the map, the location of AgriMet station and the time-series plots, the forecast of ETo for that station. In addition to the distribution of the forecasts directly from this web-based platform, the website includes an Application Programming Interface (API), which allows for data scraping of the forecasts by users

[1] The USBR, USACE, NOAA and the USGS formed the Federal Climate Change and Water Working Group (CAWWG) in 2008.

and application providers. In this way, it is not necessary to access the data via the web-browser, rather data interrogation and the forecasting data can be scripted and synthesized into other tools. In fact, one of the primary outreach efforts of this project was with Dr. Troy Peters of Washington State University. Dr. Peters has developed an irrigation scheduling tool that growers use to determine the amount of applied water to the field based on the planted crops and the crop water demand[2]. The project focused on developing the necessary API for Dr. Peters to access the forecasts and automatically include them in his irrigation scheduling tool. The irrigation scheduling tool has seen more than 1500 fields per year setup for helping manage irrigation water, and work continues with Dr. Peters to make the forecasting products available for these tools ultimately used by growers and other users.

Figure ES-1 is a screen capture of the web-based WwET4Cast forecasting tool, showing a 16-day forecast for a station (ahti) in near Ashton Idaho. The colors of the map show the spatial pattern of ETo for the selected day of 6 September 2020.



ES 1. Screen capture of the WwET4Cast forecasting tool showing the 16-day forecast for September 06, 2020 for the Ashton Idaho AgriMet station (ahi).

[2] http://weather.wsu.edu/ism

Background

The 2013 Climate Change and Water Working Group (CCWWG) identified needs for both short-term monitoring and forecast products with lead times ranging from hours to years to improve water-resource decision making. The answers sought for decision making in water-resource management are "when and how much water to use," particularly for irrigated agriculture. Accurate and timely applications of water to the field can lead to improved crop yields while saving water, time, and money. Recognizing the need to monitor and observe weather and climate conditions across the west for improving water management, Reclamation, in collaboration with the Bonneville Power Administration (BPA) partnered in 1983 to form a Cooperative Agriculture Weather Network. The network is a series of automated data-collection platforms that provide meteorological and other data for supporting the near-real-time management of Reclamation's water operations in the Pacific Northwest. Reclamation then established a dedicated network of that focused on agricultural needs, dedicated to crop-water use modeling and other agricultural applications, such as the weather data needed to model evapotranspiration. This system is referred to as the AgriMet networks. While knowing what the weather *has* been like over the past few days or weeks is certainly useful for agricultural growers and water resource managers, but arguably of greater help to these decision makers is "*what will the weather be in the future?*" Noting that users of AgriMet data rely on the station-based observations for information, the primary aim of this project was to add value to the AgriMet network by creating forecasts of the same meteorological fields that are observed at the site and used to estimate a reference evapotranspiration (ETo). Improved forecasts of ETo out 16-days can be used by growers to adapt their irrigation schedule, particularly during the shoulder season of the spring and fall, when the variability of climate is greater, and there is more risk to applying too little or too much water that can impact fertilizer application effectiveness, or miss optimal water applications during early and critical stages of growth, timing supplemental irrigation to increase yields under stressed conditions, or anticipate field preparation or harvesting conditions that might be impacted by extreme-weather events.

These evaluations are performed by applying a variety of modeling tools including several methods of estimating crop evapotranspiration (ETa) from reference evapotranspiration at an agro-meteorology stations such as those in Reclamation's AgriMet network. At these stations, a standardized reference evapotranspiration is computed from measurements of a variety of atmospheric forcings, including precipitation, temperature, solar radiation, humidity, and wind speed. Crop evapotranspiration is computed from the standard reference ETo by applying empirically determined crop coefficients. This approach has been practiced with great success to manage irrigation water scheduling.

Many studies have been performed to estimate how much water may be saved by irrigation scheduling. However, reliable weather forecasts clearly offer an opportunity for improved irrigation scheduling but the direct benefits of weather forecasts are difficult to clearly identify because water savings are confounded by differences in crop types, geographical regions, grower behavior, water delivery systems, and cross contamination of information (Rosegrant et al. 1994; Peters et al. 2008; Granfton et al. 2018; Lindstead et al. 2018). These confounding influences make it nearly impossible to establish controls for experiments. However, the savings from irrigation scheduling range from 0% to 60% with reasonable, area-wide estimates in the 15% range (Evett et al. 2006).

Most of this water saved occurs during the spring and late fall, due to more extreme weather variability; whereas in the summer, in the primary growing regions of the west, summer irrigation is dominated by constant flooding and is less reactive to the relatively benign, warm weather conditions.

This joint project, convening Reclamation and NCAR, built a web-based platform that provides daily ETo estimates and forecasts, computed from agricultural meteorological station monitoring data, along with forecasted meteorological variables, including minimum and maximum air temperature, relative humidity, precipitation, net solar radiation, and wind speed. These variables are used to estimate and forecast daily ETo. The web-based platform provides daily ETo forecasts 16-day, 60-day, and 6-month seasonal lead times at AgriMet and California Irrigation Management Information System (CIMIS) stations. The 16-day lead-time forecasts are based on downscaled meteorological forecasts from NOAA's GFS model to compute daily ETo on a daily update cycle. By providing computed ETo from measured sensor data with the forecasted ETo from the GFS model, the combined dataset provides users with a retrospective of recent ETo estimates that can be used to compute recent crop consumptive uses; and forecasts of ETo, which can be used to make medium-resolution irrigation scheduling decisions. The forecasts are updated daily and include an ensemble representation of the forecasts. Because the update cycle is daily, the forecast uncertainty is minimized.

In addition to 16-day forecasts, the WwET4Cast offers users longer-term seasonal ETo outlooks along with other important meteorological variables, such as temperature, humidity, and wind speed. The WwET4Cast tool offers the user options to output the ETo results in batch mode using a URL API so forecast updates can be scheduled to occur automatically, and the data can be downloaded in a variety of formats that can be used as inputs to crop consumptive use models, for example.

Project Development

For this project, NCAR collaborated with the California-Great Basin Office of the Bureau of Reclamation to work with both the AgriMet (Columbia-Pacific North West Region) and CIMIS (California Great Basin Region) networks to complement their meteorological data with forecasts of reference evapotranspiration (ETo) and other meteorological variables at both daily, sub-seasonal, and seasonal time scales. As a representative of the user-side, Western Washington University's Dr. Troy Peters participated in the activity to improve the water-demand forecasts beyond temperature and precipitation. Dr. Peters has developed an Irrigation Scheduler app3 that monitors crop-irrigation requirements. Forecast values have been drawn from NOAA's Global Forecast System (GFS). The new ETo forecasts from this new activity are more detailed and extended in their temporal scale.

High-resolution global coupled climate models (GCMs) are recognized as promising tools that may provide additional climate information for improving sub-seasonal (16 days or less) and seasonal climate prediction (one month to 12 months), and to better understand regional climate variability and climate processes. The advantage of a dynamical climate model is that it is grounded in the

[3] http://weather.wsu.edu/ism/

physics of the oceans, atmosphere, land, ice, and their complex and multiple interactions. In theory, an accurate representation of the state of these components of the climate system, commonly referred to as their "initial condition and boundary conditions," should theoretically allow one to forecast the future climate state more accurately. Complications arise, however, from the fact that the climate system is inherently chaotic, as atmospheric predictability depends on the internal dynamics of the atmospheric and the variability of the boundary conditions (land, water, and ice). This observation was most famously observed by Edward Lorenz (Lorenz 1965[4]), in which he formulated equations that describe the atmospheric system and showed that a minute perturbation in the initial conditions would result in dramatically different future states. This became known as the "butterfly effect."

Studies have shown that high-resolution GCMs have the potential to skillfully forecast seasonal rainfall, including rain events influenced by complex topography, and forecast initiation of tropical cyclones (TCs) and their tracks at Sub-seasonal to Seasonal (S2S) time-scales, thus, forecasting high-impact weather/climate extremes (Froude et al. 2013). Therefore, a goal of this project is to demonstrate how dynamical models can be used to provide added value to sub-seasonal and seasonal forecasts at the agro-meteorological observation stations throughout the western U.S.. NCAR developed and deployed a web-based visualization tool for the sub-seasonal and seasonal forecasting products. This data portal displays the model output (images, station data, etc.) from Global Climate Models (GCMs) resulting in seasonal climate forecast products across the western U.S. Since initial prototype development, the next generation of the NOAA GFS model has been deployed and the data archive locations have changed, prompting the project to update system components to ingest data in real time.

The West-wide Evapotranspiration Network Forecast (WwET4Cast) project developed a web-based platform for forecasting the key meteorological variables used in estimating crop water demand and the impacts of weather and climate on crop growth. There are many atmospheric factors that influence crop evapotranspiration and crop yield. Temperature itself can have an impact on crop growth during important stages, so key variables being forecast are daily minimum and maximum temperatures.

Dr. Michael Tansey, Reclamation PI, collaborated with NCAR throughout the project to guide the project's usability and credibility of the forecast products for Reclamation and other end users. Together, we obtained the necessary data to perform the various forecasts and statistical analyses for monitoring and forecasting ETo. The agro-meteorology station observations were used to quantitatively evaluate the forecast reliability, skill, and uncertainty. NCAR was responsible for the web-based software development and modifications, as well as the statistical analyses and computational algorithms needed to obtain data inputs, generate outputs and verify the results.

[4] E.N. Lorenz (1965) A study of the predictability of a 28-variable atmospheric model, Tellus, 17, 321-333.

Research Methodology

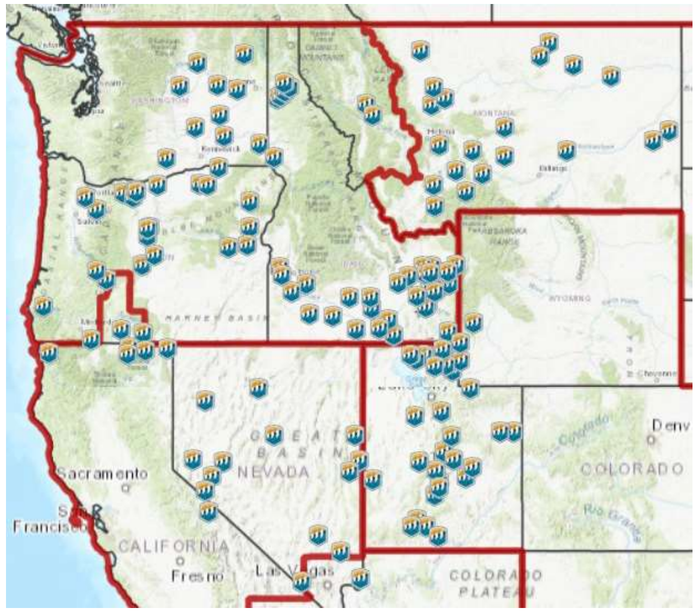
A primary motivation for developing an ETo forecasting system was to add value to existing meteorological station networks across the western U.S. In a recent, informal survey by Dr. Troy Peters[5] conducted at a digital agriculture summit, stakeholder groups voiced opinions that meteorological information in support of irrigation practices needs to be simple and intuitive. Perhaps more importantly, what has already happened (history) is much less meaningful to them than what is going to happen (forecasts). This simply stated need for forecasts is a key motivator of the ETo forecasting system developed by the project. Good irrigation management saves water, energy, fertilizers, labor costs, and helps growers get better yields, thereby strengthening rural economies and improving environmental water quality. For growers, the real financial benefit of good irrigation management is an increase crop yields and corresponding economic benefits. The intent of this project is to potentially improve crop water use efficiency and yields. The project outcome is a useful, and easy-to-use web-based data portal where irrigators, growers, and water-resource managers can find forecast information to help improve the management of their water resources. Indirect benefits of providing ETo forecasts will be improved water management resulting in more water stored in reservoirs or more water available for the environment that may enhance streamflow, particularly in low-flow conditions that would benefit fisheries, as one example.

The station-based, ETo forecasts rely on operational weather forecasts made by the National Oceanic and Atmospheric Administration (NOAA) U.S. National Weather Service, including both short-range forecasts made out 16-days from the Global Forecast System (GFS) model and the long-range Climate Forecast System (CFS) model, which goes out beyond a full year. These GCMs generate forecasts on a daily basis, and in fact, generate at least four individual forecasts per day. Because forecasts of the future weather are uncertain, these multiple daily forecasts can be used to represent the uncertainty of the forecasts, which is commonly referred to as the "ensemble." These ensemble forecasts are used in the WwET4Cast system to express the uncertainty of the forecast, with the forecast presented as a projected range that includes the mean forecast, which is the average of each ensemble member for the given time of the forecast.

The project identified two meteorological networks to add initial weather forecasting capability, and include the AgriMet network managed by Reclamation and the California Irrigation Management Information (CIMIS) network managed by the State of California Department of Water Resources (DWR). The WwET4Cast forecast project ingested real-time observational data and the historical archive from the AgriMet and CIMIS networks for the full complement of meteorological data needed to forecast reference evapotranspiration (minimum and maximum temperatures, wind speed and direction, surface pressure, humidity, and shortwave radiation). In addition, the AgriMet stations provide an daily ETo estimates themselves, which are being used to verify the forecasts.

[5] Personal Communication, 9 October 2020.

The Agriculture Mesonet (AgriMet) Network



The AgriMet network comprises over 70 weather stations located throughout the Pacific Northwest, three stations of which are operated by the NOAA Air Resources Laboratory in Idaho Falls. Over 20 stations east of the Continental Divide in Montana are managed by the Bureau of Reclamation Great Plains Region. The network is sponsored by the Reclamation with additional support from the USDA Agricultural Research Service, the USDA Natural Resources Conservation Service, land grant universities, the Cooperative Extension System, electric utilities, power companies, and other public and private agencies, and organizations. In addition to the AgriMet network itself, the data service hosted by the Reclamation Columbia-Pacific Northwest Region includes additional networks from University of Utah and the Desert Research Institute's (DRI) Mesonet networks. The inset map shows the AgriMet network as deployed in the WwET4Cast web-based system.

Real-time AgriMet data is transmitted from individual stations to Reclamation's receive site in Boise, Idaho through the Geostationary Operational Environmental Satellite GOES-8, GOES-9 and DOMSAT satellites. Each station transmits its data hourly. Data collection intervals within are dependent on the specific sensor equipment at each station. The data are processed on minicomputers running the OpenVMS operating system at the Boise Regional Office, then made available on via a web page, https://www.usbr.gov/pn/agrimet/agrimetmap/agrimap.html. We note that the AgriMet network and this web-based distribution instrument includes several additional observational networks, such as the DRI, and the Utah Climate Center Mesonet, with the total available networks shown on the above inset image.

The WwET4Cast server downloads the same weather model variables as measured by AgriMet network and uses station observations to bias correct weather model variables to represent station conditions. It is important to note that an agro-meteorological station ideally has a large, well-maintained short grass or alfalfa area surrounding the station. This area is necessary to ensure the meteorological observations (eg temperature, humidity, etc) are representative of conditions occurring in an irrigated field. This requirement is necessary because crop water use (ETa) is computed as the product of ETo and empirically determined crop specific coefficients (Kc) which were developed based on calculated ETo and measured ETa (ie Kc = ETa / ETo). The WwET4Cast procedure for calculating ETo is described in the Reference Evapotranspiration section below.

The California Irrigation Management Information System (CIMIS)

The California Irrigation Management Information System (CIMIS) is a large network of stations across the state of California that is managed by the DWR. CIMIS collects automated weather data at 145 stations on a minute-by-minute basis, with hourly data reflecting the previous hour's 60 minutes of readings. CIMIS retrieves data from the stations about every hour. CIMIS data processing involves checking the accuracy of the measured weather data for quality, calculating reference evapotranspiration (ETo) and other intermediate parameters, flagging measured and calculated parameters, and storing the data in the CIMIS database. The CIMIS system calculates ETo for standardized grass or alfalfa surfaces over which the weather stations are located and can be used to compare the forecasts made by the WwET4Cast system. The WwET4Cast server downloads the same meteorological variables as the CIMIS network, and bias corrects them into the format for use in the ETo calculation. The inset map shows the CIMIS network as deployed in the WwET4Cast web-based system.

The Global Forecast System (GFS) 16-day, bias-corrected ETo Station Forecasts

The global forecast system model version 4 (GFS[6]) data are downloaded and archived on the NCAR data server, where a four-member lagged ensemble is used to express the amount of uncertainty in the forecast on a day-to-day basis. The GFS 16-day forecast data are on an approximate 25-km grid, with daily forecast data generated for the same meteorological fields as the observations, which are used to estimate daily ETo. The GFS forecast data are extracted for the corresponding grid cells of the meteorological station data (AgriMet and CIMIS), and are bias corrected according to these observations. A bias will almost certainly exist within the relatively coarse scale of the GFS data, because sub-grid variability is simply not represented, particularly in regions of complex topography. In this way, local ETo ensemble forecasts for the individual stations of the AgriMet and CIMIS networks can be more accurately forecast.

The medium-resolution forecasted daily ETo requires appropriate downscaling of the larger-scale outputs of the GFS model to the local scale of the agro-meteorology data. This is important because the GFS forecasts are likely biased when compared with the station meteorological data because the

[6] NCEI DSI 6182, NCDC-GFS_FORECAST, gov.noaa.ncdc:C00634

computational grid boxes of the GFS model can extend from valley floors, into higher topographic regions, with strong climate gradients. These biases are taken into account on the server side of the WwET4Cast tool by tracking the 8-day mean of each observational variable against the 8-day GFS grid-cell average. A bias correction is then made that correlates the large-scale field to the local-scale observation, which is used in the local-scale forecast. Once these analyses are completed, the downscaled GFS outputs are used to determine the local meteorological variables used to forecast ETo using the ASCE Penman Monteith set of equations (see below).

Each GFS meteorological forecast variable is independently bias corrected based on a ratio of the running average of the previous forecasts' initial time values and the observations for the same day. The averages are based on a look-back of the previous *n* days, which is a user defined variable on the input parameters. For each field, this ratio is applied to the GFS-forecasted value out to the full 16-day forecast length. The look-back length for the bias correction is typically 10 days, with bias corrections made for each meteorological variable input to the ETo calculation. These include minimum, maximum, and mean temperature; wind speed, humidity, and radiation. Temperatures are first converted to Kelvin so that a ratio of the GFS to observations can be made directly, and then reverted back to Celsius to produce the final ETo estimate. In cases where the station failed to make measurements over the previous *n* day lookback period, and thus no bias correction information is available, the ETo forecast simply corresponds to the underlying raw data of the GFS forecast.

The Climate Forecast System (CFSv2) Seasonal Outlooks

The NOAA's Climate Forecast System (CFSv2[7] or CFS hereafter) seasonal outlooks are automatically downloaded onto a NCAR server on a daily basis (CFS, Saha et al. 2014[8]), generating four ensemble forecasts per day. The CFS forecasts extend to more than one year, and thus, with forecasts issued daily, a large lagged ensemble can be generated if the forecasting updates are made say, on a weekly basis. With a four-member ensemble available each day, if the forecasts were aggregated on a weekly basis, the number of forecast ensembles would be 28. For the WwET4Fcst system, the lagged ensemble is made by using the four forecasts per-day, assembled for the past seven days, resulting in a 28-day lagged ensemble, which is generated on a daily basis. These seasonal forecasts extend to nine months.

While there is overlap with the GFS-based sub-seasonal forecast time scale, the update frequency and objectives based on the CFS outlooks are somewhat different. Rather than daily forecasts, the near-term products of the seasonal forecasts are aggregated at 1) 10-day intervals for the 60-day forecasts, and 2) monthly time intervals for the longer-term seasonal outlooks that extend to nine months. The emphasis of these longer forecasts or "outlooks" is to give the user a sense of whether or not there is consensus being generated by the CFS forecasts of conditions being above or below the historical average condition. For this reason, we did not provide station-based estimates of the CFS seasonal outlook products; rather, we presented these as outlooks on the WwET4Cast website relative to the historically observed range of the particular meteorological variable. Thus, one can compare the outlooks not only for ETo, but for the other meteorological variables used in the ETo calculation (temperature, humidity, wind speed, and radiation). Both the outlook and the historical range of the meteorological variable are available across the western region of the U.S. in the

[7] NCEI DSI 2001_01, gov.noaa.class:NCDC-CFSV2_FORECAST, gov.noaa.ncdc:C00877

[8] Saha S. et al., 2014: The NCEP Climate Forecast System Version 2. J. Climate, 27, 2185-2208.

WwET4Cast web-based inspector, for both the 60-day CFS and 9-month CFS outlooks. Next, we describe the reference evapotranspiration variable being forecast within the WwET4Cast system.

Reference ETo

The WwET4Cast ETo forecasts are based on the well-known Penman-Monteith (PM) equation (Monteith 1981). The PM equation describes evapotranspiration under optimum water, soil and biological growth conditions. This evapotranspiration is referred to as the reference (standardized) evapotranspiration (ETo) when the aerodynamic and canopy resistances parameters are defined by specific values characteristic of a well maintained short-grass or alfalfa crop (Allen et al 2005) and is given in Eqn 1.

$$\mathbf{ETo} = \left\{ \frac{\Delta(\mathbf{R_n} - \mathbf{G}) + \mathbf{K_t} \boldsymbol{\rho}_\mathbf{a} \mathbf{C_p} \frac{(\mathbf{e_s} - e_a)}{\mathbf{r_a}}}{\Delta + \boldsymbol{\gamma}(\mathbf{1} + \frac{\mathbf{r_s}}{r_a})} \right\} / \boldsymbol{\lambda} \boldsymbol{\rho}_\mathbf{w} \qquad \text{(Eqn 1)}$$

Where in SI units the terms of the equation are given by:

ETo = Reference evapotranspiration (mm d^{-1})

$\mathbf{R_n}$ = Net solar radiation (MJ m^{-2} d^{-1})

G = Soil heat flux (MJ m^{-2} d^{-1})

$\mathbf{e_s}$ = Saturation vapor pressure of the canopy (kPa)

$\mathbf{e_a}$ = Actual vapor pressure of the surrounding atmosphere (kPa)

$\mathbf{r_a}$ = Aerodynamic resistance (s m^{-1})

$\mathbf{r_s}$ = Canopy resistance (s m^{-1})

$\boldsymbol{\Delta}$ = Slope of the saturation vapor pressure-temperature curve (kPa °C^{-1})

$\mathbf{C}_p$ = Specific heat capacity of moist air (MJ kg^{-1} °C^{-1})

ϱ_a & ϱ_w = Mean air and water density respectively (kg m^{-3})

$\boldsymbol{\gamma}$ = Psychometric constant (kPa °C^{-1})

$\boldsymbol{\lambda}$ = Latent heat of vaporization (MJ kg^{-1})

K_t = 86,400 s d^{-1}

The terms in Eqn. 1 depend on both biological and meteorological conditions. It is worth noting that air temperature does not appear directly in the PM equation. The ASCE PM method (Allen et al. 2005) describes relationships between several variables in Eqn. 1 and daily or hourly temperatures. Temperature-dependent variables include the latent heat of vaporization λ, the mean air density, ϱ_a, slope of the saturation vapor pressure-temperature curve, Δ, and the psychometric constant, γ. The net radiation term, *Rn*, also depends on temperature through the effect of surface temperature on outgoing long-wave radiation. The saturation vapor pressure, e_s, is also a function of air temperature and affects the stomatal vapor pressure, which drives the diffusion of water vapor from leaves. The vapor pressure deficit (VPD) defined as the difference between e_s and e_a typically increases with increased air temperature. In the PM equation, an increase in the VPD results in an increase in ETo.

Other meteorological influences on crop ETo include the effects of the canopy albedo on the reflection of incoming shortwave radiation, the influence of wind speed and crop height on aerodynamic resistance, r_a, and the effects of stomatal conductance and canopy development typically expressed in terms of the leaf area index (LAI) (m^2 leaf area per m^2 soil surface) on canopy resistance, r_s. Kimball (2007 and 2010) performed a temperature-sensitivity analysis on some of the meteorological and plant variables used in the ASCE hourly PM equation (Allen et al. 2005) using 1987 data obtained from a weather station in Maricopa, AZ. Results from this study are presented in Table 1. The sensitivity of ETo to temperature is greatest of all the variables considered. As discussed above, temperature affects many of the variables in the PM equation, but its effect on the vapor pressure deficit (e_s - e_a) is most likely the main reason for its greater significance in the results. However, increasing atmospheric humidity, e_a, reduces ET by decreasing the VPD. Furthermore, it worth noting that temperature effects on growth and LAI of non-reference crops are not really represented in this analysis because reference crops are assumed to have a constant canopy height and LAI throughout the growing season, which is not representative of most agricultural crops.

Table 1. Sensitivity of the ASCE Hourly PM Equation to Weather and Plant Variables

Weather or Plant Variable	ET Sensitivity (% Change in ETo)	
	Summer Day	Whole Year
Temperature effect per Δ°C at constant absolute humidity	2.39	3.44
Solar Radiation effect per Δ% Rs	0.58	0.40
Atmospheric vapor pressure effect per Δ% e_a	-0.16	-0.40
Wind effect per Δ% U	0.29	0.38
Stomatal conductance effect per Δ% gs	0.08	0.16
LAI effect per Δ% LAI	0.08	0.16

Higher temperatures also have the potential to affect crop phenological characteristics that correlate to crop ET. For perennial crops, increased warming will continue lengthening the growing season, which will tend to increase total annual ET. For annuals, earlier warming may cause a shift in the growing season towards earlier in the year. These shifts may or may not increase crop-water use. As discussed above, more rapid growth due to warming may shorten the actual growth period, resulting in reduced water consumption for some crops. However, for those crops (either annual or perennial) exhibiting photoperiod sensitivity, earlier growing season initiation may result in slower growth in the spring when solar radiation in the northern hemisphere is less intense and consequently reduces ET during the early vegetative growth stage. Furthermore, growing season shifts may result in crops being exposed to other climatic conditions such as increased precipitation and/or humidity or decreased wind speed, which would also tend to reduce crop ETo. These are the key aspects of the ETo calculation considered when we generate forecasts.

Temperature is a major factor in determining atmospheric humidity. As temperature increases, the rate of evaporation from the oceans results in higher atmospheric humidity. Increased atmospheric humidity also reduces the intensity of solar radiation (Rs) reaching the earth's surface. Although this reduction is not large, it reduces the energy available for photosynthesis as well as ET. Changes in atmospheric humidity may also affect the ability of plants to produce biomass and yield by changing the vapor pressure deficit (VPD) which is defined as the difference between the stomatal vapor pressure (es) and vapor pressure of the surrounding atmosphere (e_a). Because the saturation vapor pressure is a strongly nonlinear function of temperature, e_s typically increases more rapidly than e_a especially as the ambient temperature increases. Thus, increasing temperature typically causes an increase in VPD. If the increase in VPD remains below plant-specific thresholds, an increase in VPD results in increased ET. However, when the threshold is exceeded, ET may decrease in relation to the VPD increase. For some crops, growth may also be affected because increasing VPD may decrease the crop's radiation-use efficiency (RUE) resulting in less growth. Table 1 summarizes information about temperature dependence of various life-cycle phases for some major agriculture crops grown in the Reclamation project areas and for which forecasts of meteorological conditions, including ETo, would be potentially beneficial.

Table 2. Temperature (^{0}C) Dependence of various Life Cycles Phases for some Major Agriculture Crops

Crop	**Base[1] Temp Veg Prod**	**Opt[2] Temp Veg Prod**	**Base[3] Temp Reprod**	**Opt[4] Temp Reprod**	**Opt Temp Range Reprod Yield**	**Failure Temp Reprod Yield**	**% Yield[5] Change Per ^{0}C increase**
Corn	8	34	8	34	18-22	35	-3.3
Cotton	14	37	14	28-30	25-26	35	-4.8
Rice	8	36	8	33	23-26	35-36	-10
Wheat	0	26	1	26	15	34	-5.4

Footnotes:

1. Base Temp Veg Prod = Base temperature for vegetative production
2. Opt Temp Veg Prod = Optimum temperature for vegetative production
3. Base Temp Reprod = Base temperature for reproductive phase
4. Opt Temp Reprod = Optimum temperature for reproductive phase
5. Estimated yield changes in North America relative to beginning of 21st century

Source: Synthesis and Assessment Product 4.3, Tables 2.2 and 2.6 (USGCRP, 2008)

An evapotranspiration software library (Guo et al. 2016) was used to calculate the daily PM evapotranspiration, according to Eqn 1 within the forecasting workflow, with the ETo forecasts made out to lengths of 16 days for the GFS forecast, and 60 days and 9 months from the CFS outlooks. The details of this process are presented below.

The Web-Based, WwET4Cast ETo Inspector

The West-wide ETo Forecast Network Inspector (WwET4Cast) is a web-based tool designed for stakeholders, growers, irrigators, Reclamation water managers, and others to be informed of the likely Sub-Seasonal to Seasonal water-demand forecasts and outlooks given by ETo forecasts. WwET4Cast is currently deployed on an NCAR server[9] at the time of this report. This tool is intended to provide quick insight into different forecasts / outlook fields, within a range of

[9] https://hydro.rap.ucar.edu/HydroInspector/WW_ETfcst/ Accessed 01 March 2021.

timescales, and can also be used to download ETo forecasts for use in other models or applications. Figure 1 shows a screen capture of the web-based WwET4Fcst inspector tool demonstrating a 16-day, GFS-based forecast for the Ashton AgriMet station in eastern Idaho.

The intent is to provide daily to monthly-level insights into a number of preselected forecast fields, chiefly the ETo forecasts, and to augment the map-based fields with useful additional information to provide context for interpretation. However, WwET4Cast is not necessarily the central tool for detailed analyses or the main interface for actual practitioners. Rather, it is an interface to help inform end-users, outreach to the community about the forecasting capability, and monitor the underlying data infrastructure to ensure it is operating properly and identify potentially important weather situations that warrant special attention. Via an Application Programming Interface (API), the WwET4Cast has the ability to automatically download forecasts and outlooks that could serve as input to other tools and/or models for quantifying ETo and water demands. Details of the browser-based interface and the capabilities of the API are detailed in the appendix of this report.

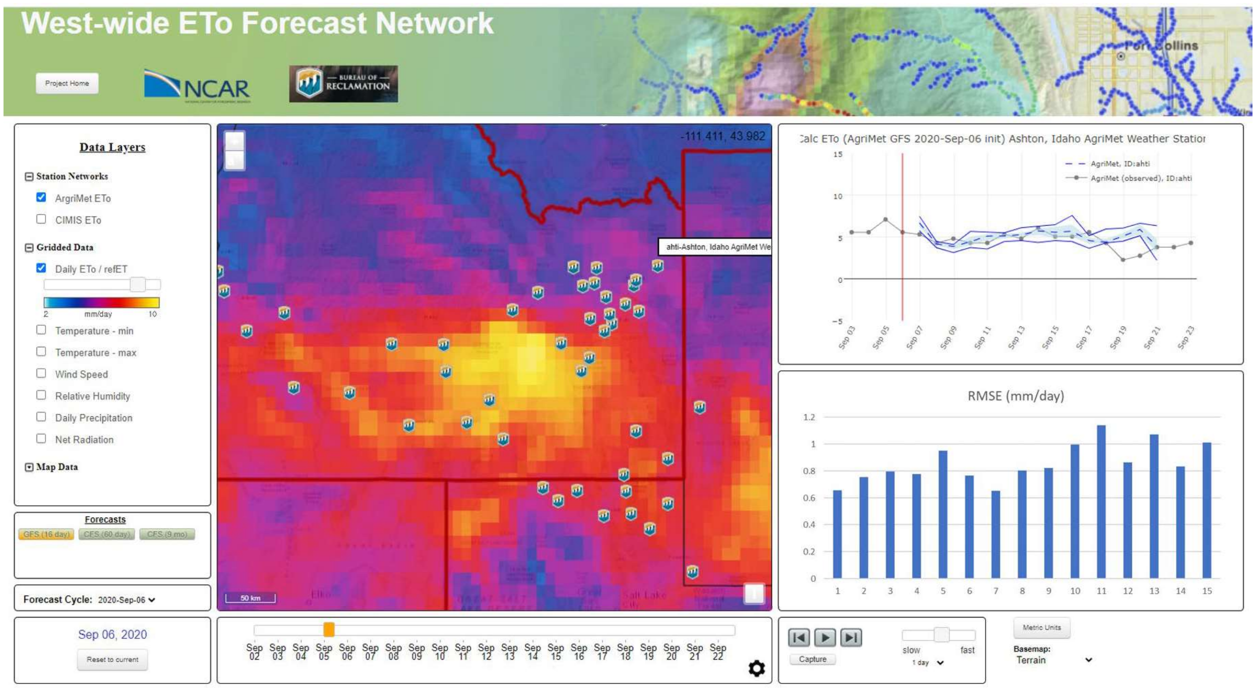


Figure 1. Screen capture of the WwET4Cast forecasting tool showing the 16-day forecast for September 06, 2020 for the Ashton Idaho AgriMet station (ahti). The colored map shows the spatial pattern of daily ETo over southern Idaho, where brighter colors are higher values. The top-right time series is the 16-day forecast of ETo for the station, and the vertical redline is the initiation time of the forecast. The bar-plot on the bottom-right is the daily forecast bias that has been observed at this station for the past 18 forecast days (mm/day).

Operational forecasting requires organizing, managing and curating significant amounts of observational and model-based data. The WwET4Cast inspector provides quick access and insight into forecast datasets with both map-based overviews of selected time slices of the forecasts, as well as simple, location-based visualization of relevant time series of key atmospheric variables. In order to provide broader context for the interpretation of the forecasts, WwET4Cast offers two additional visualization elements, which are the background climatological state at both the monthly and seasonal levels that gives the user a sense of the magnitude of the forecast relative to the historic conditions, as well as a metrics on the prime dynamical drivers of the forecast including minimum and maximum temperature, wind speed, relative humidity, solar radiation, and precipitation.

Results

An example 16-Day Forecast

As a working example, we have chosen a forecasting period from August 20th to September 5th, 2020 to demonstrate and interpret an ETo forecast. Figure 2 shows the spatial pattern of ETo across the western U.S., as estimated by the GFS model for the 20th of August. This is not a forecasted estimate, rather a "best estimate" of the actual ETo for that day derived from the current time of the forecast. Note the higher values of ETo over the Central Valley of California, central Nevada, and Southern Idaho. The higher ETo in Idaho generally corresponds to the lower elevations of the Snake River Valley. It is clear from the figure that the majority of the AgriMet stations in this region correspond to intensive agriculture and irrigation in Southern Idaho. Figure 2 shows that the Malta AgriMet station in southeastern Idaho (AgriMet code malt), which has been highlighted in the WwET4Cast web-based inspector. This station and location (42.43 lat and -113.42 long) will be used to demonstrate the 16-day, 60-day, and 12-month forecasts.

August 20, 2020 ETo (GFS Gridded Estimate)

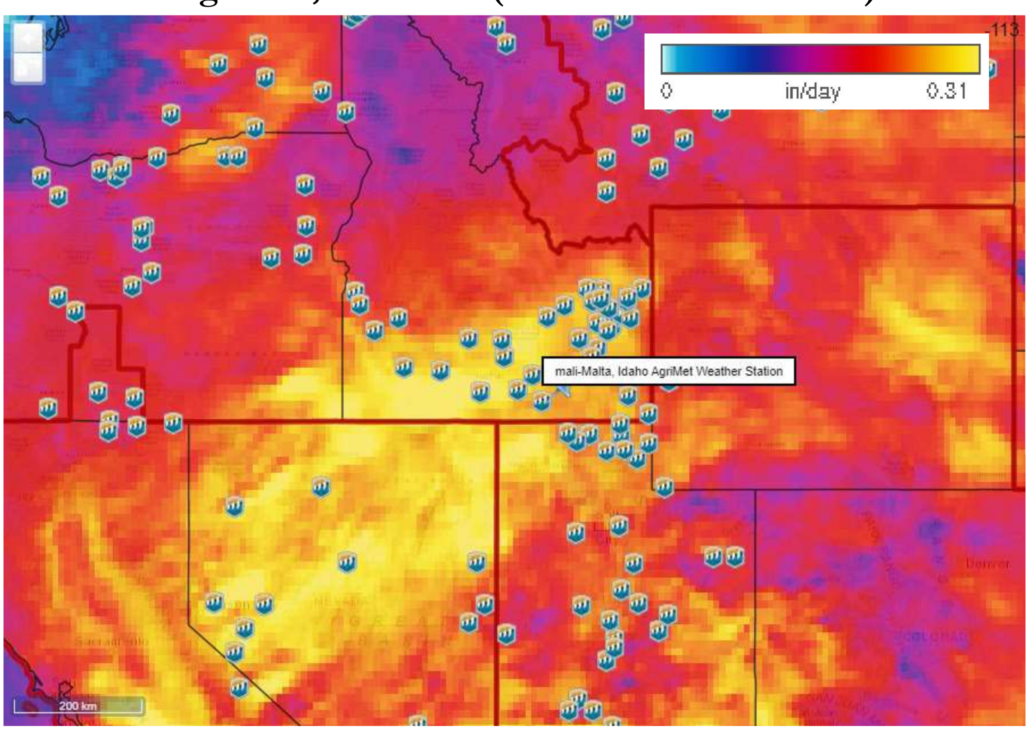


Figure 2. A screen capture showing the spatial pattern of ETo across the north-western U.S., which includes the location of the AgriMet network stations. The Malta station has been highlighted. The colors represent the estimate of ETo based on the raw GFS forecast values for 20 August, 2020.

Figure 3 shows the Malta station selected and the range of the ETo forecasts made for August 20th out to September 4th. Including August 20th, this represents a 16-day forecast. On the inspector tool, we hovered over the September 3rd forecast, which shows a forecast range of 0.147" to 0.175", and a mean value of 0.156 inches. The forecast range for this particular station and time period is relatively small.

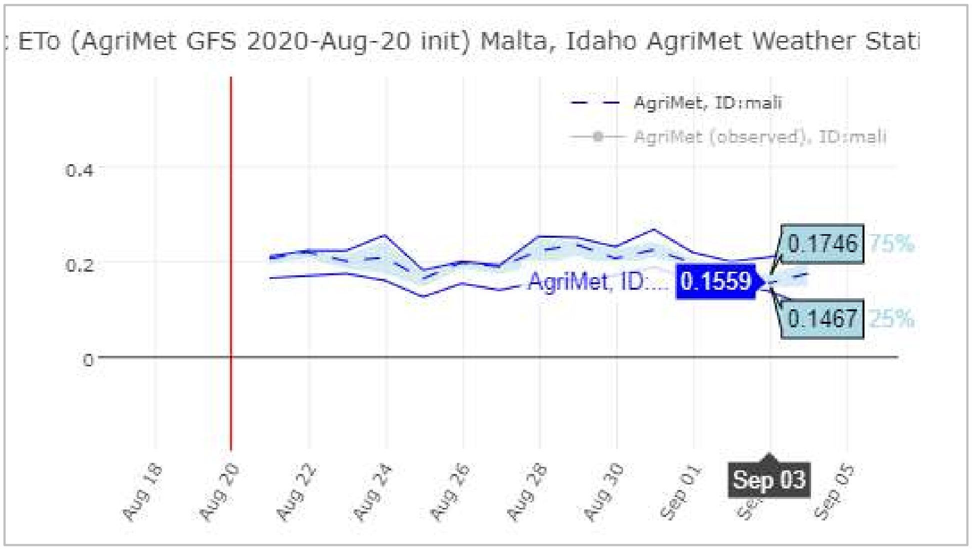


Figure 3. The vertical red line in the figure denotes the initiation time of the forecast, while the solid blue lines are the minimum and maximum value of the forecast and the shaded blue area is in the inter-quartile range of the forecast.

Because we can observe what happened at this station, now that the forecasting period is complete, we can qualitatively assess whether there was any skill in the forecast by adding the observation of ETo to Figure 3 and comparing the forecasts. This additional observational information has now been included in Figure 4

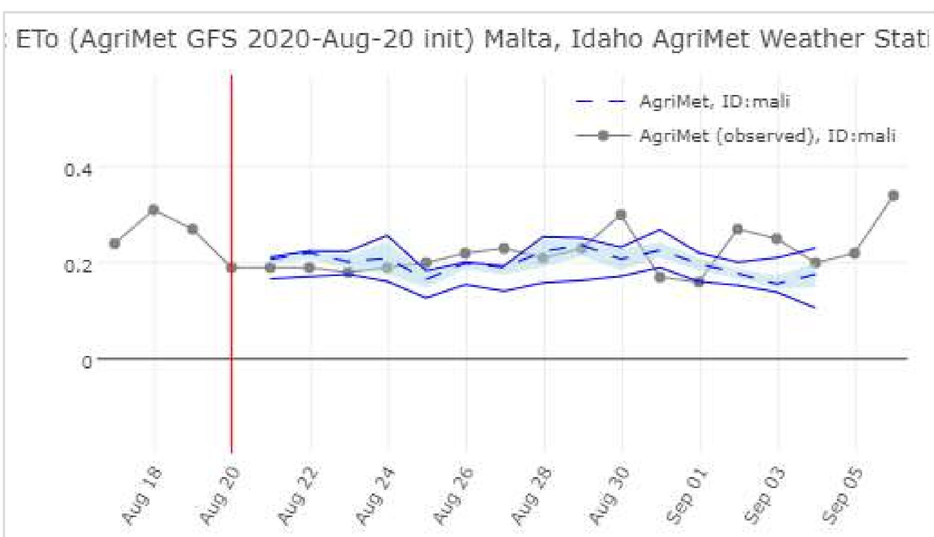


Figure 4. Same as Figure 3, but now including the observed ETo as measured at the Malta AgriMet station for the period Aug 18th through September 6th.

If one takes note of the increasing ETo values observed on September 6th and 7th, we advance the forecast cycle from the 20th of August to the 22nd of August (2 days forward), and note that some of the ensemble members forecast higher ETo values at the end of August, but still miss the high ETo values in early September

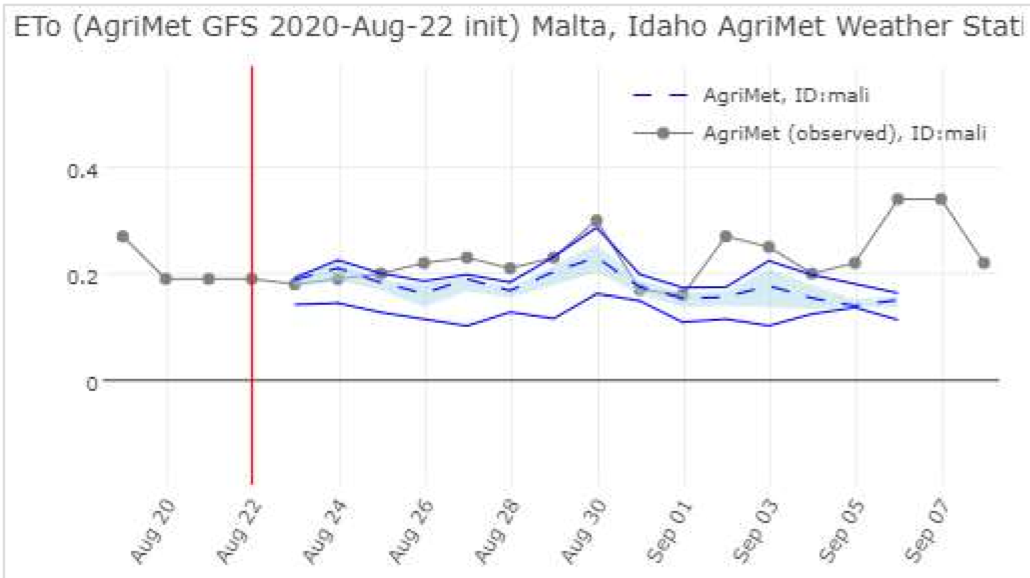


Figure 5. Same as Figure 4, but now with the forecast time moved forward by two days. Note the high ETo values September 6th and 7th, which at this forecast lead time are not well captured.

After moving the forecast cycle forward to the next week of 30th of August, Figure 6 shows that the higher ETo values of September 6th and 7th become more pronounced within the forecast. Note that after this high-ETo event, there are forecasts that remain above the observed (Sept 8th, 9th, and 10th), but some of the forecast ensembles did reflect this lower estimate.

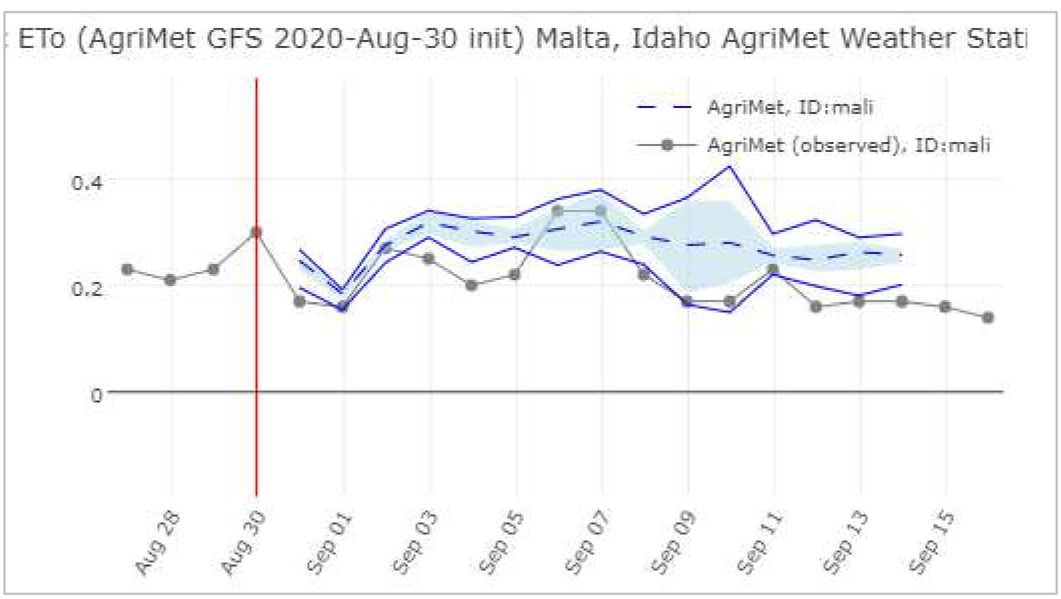


Figure 6. Same as Figure 4, but now with the forecast time moved forward to 30 August, 2020. Note the high ETo values September 6th and 7th, which are generally captured, with more forecast spread.

While the WwET4Cast allows the user to extract station-based forecasts, one can also extract forecasts for any point in the GFS domain displayed on the map to derive a raw GFS forecast of ETo. Figure 7 shows the forecast for the corresponding grid point of the Malta station, as well as the ETo forecasts made on August 30th, with elevated estimates about one week out (September 7th), as shown by the green bounded region, which can be compared with the historical average ETo derived from the GCM reanalysis data shown in gray. The gray region can be thought of as the climate average and the inter-quartile range of ETo for the given day and suggests the potential range of ETo range for the period shown. For the one-week forecast issued on August 30th for September 7th, the mean of the daily raw ETo GFS forecast is 0.24 inches, while the bias-corrected estimate of ETo at the Malta station is 0.32 inches. The observed value of ETo on 7th September was 0.34 inches. In this case, the bias-correction procedure improved the one-week forecast by 30%. Also, the forecast on August 30th suggests elevated ETo for the following week.

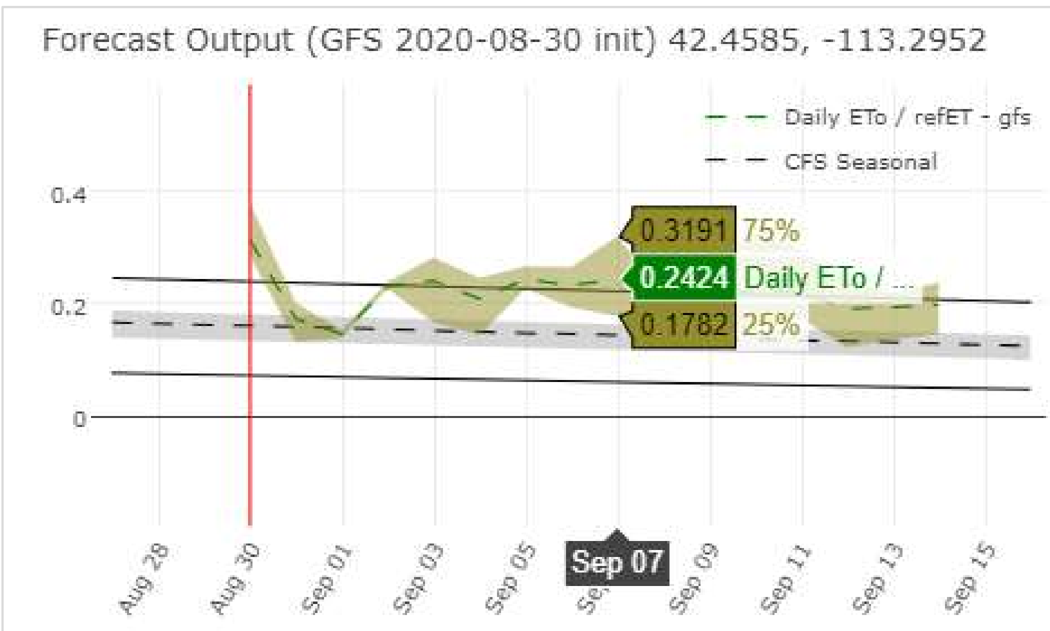


Figure 7. ETo forecast generated from the raw GFS data for a forecast initiated on 30 August 2020. The green bounded region is the range of the ETo forecast, with the green line the ensemble mean. The black and gray plots represent the historical range of the GCM based estimate of ETo for the dates shown.

An Example 60-day Outlook

The WwET4Cast inspector also includes the generation of ETo forecasts at seasonal timescales, based on forecasts made by the Climate Forecast System (CFS) model. The forecast cycle we examine begins on the 12th of May, 2020. Figure 8 shows the time series of the observed daily ETo from the beginning of April through the end of June for the Malta AgriMet station. This pattern of greater variability into late spring is observable in the surrounding AgriMet stations as well (not shown). Surprisingly, there is no strong seasonal trend in ETo from May through the end of June, but there is considerable day-to-day weather variability in the later part of the spring period.

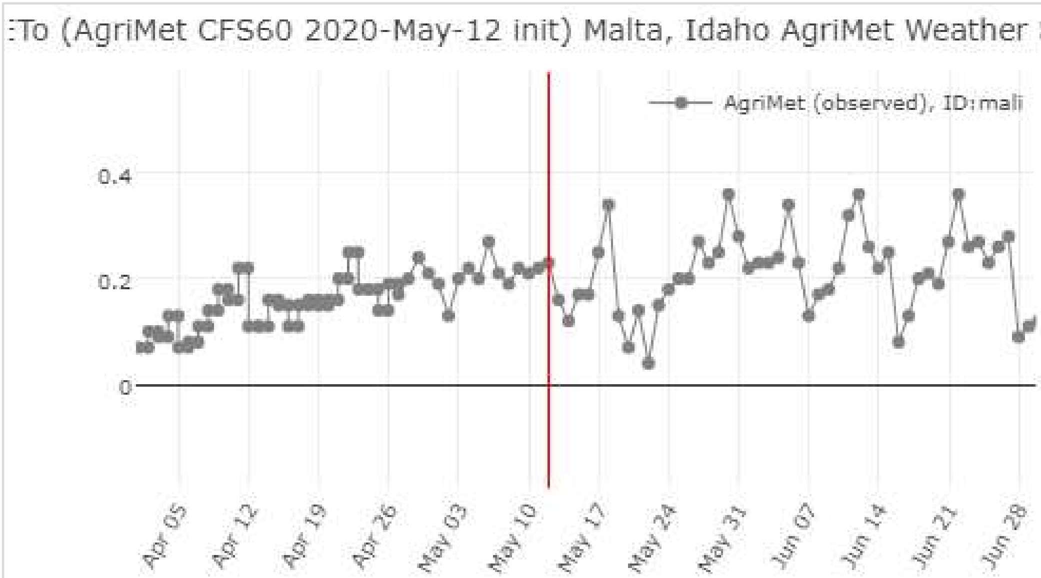


Figure 8. The observed ETo for the period of April 1st through June 30th, 2020. ETo.

Figure 9 shows the 10-day forecasts of ETo for the grid point in the CFS domain corresponding to 42.1° N and -113.71 ° West. Note that these forecasts are generated for each day, based on the four ensemble forecasts available for that day. This 60-day outlook shows that there is a slightly increased likelihood of an increase in ETo over the forecast period relative to the historically observed ETo. Given the extreme nature of the observed variability of ETo as shown in Figure 8, the value of the 60-day outlook as shown in Figure 9 would need to be further explored.

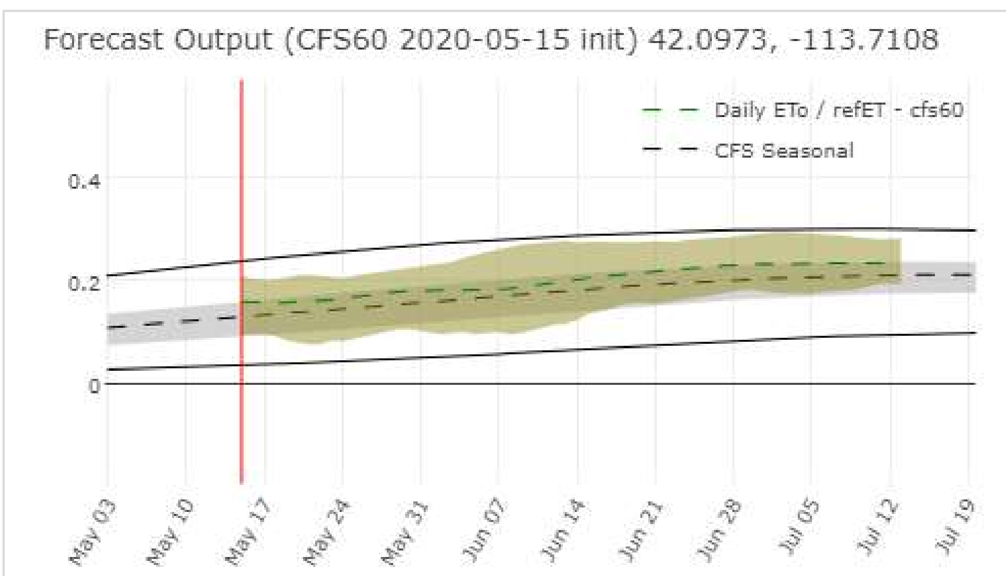


Figure 9. The projected range of forecasted ETo from the GFS model for the given location, where the green region is the inter-quartile range and the dashed green line is the daily average. The gray lines show the range of the observed value over the past 20-year period.

In addition to the forecasting of ETo, all of the other meteorological variables included in the forecasting system are available for exploration (minimum and maximum temperature, wind speed, relative humidity, precipitation, and net solar radiation). Figure 10 shows the outlook for the same period as was shown in Figure 9, but only for the minimum temperature and relative humidity fields from the CFS model. Interestingly, the outlook shows warmer temperatures and considerably lower relative humidity over this period, which explains the elevated outlook of ETo as shown in Figure 9. Net Radiation is near the climatological mean suggesting that this much cloud cover over the period is not unusual, although wind speeds are below the climatological average. Note there are slight differences in the lat-lon point that is reported in the plot. This is because the plot is generated by selecting a point on the digital map, which can differ depending on user selection. Note, however, that the selected point always represents the same grid point of the CFS model.

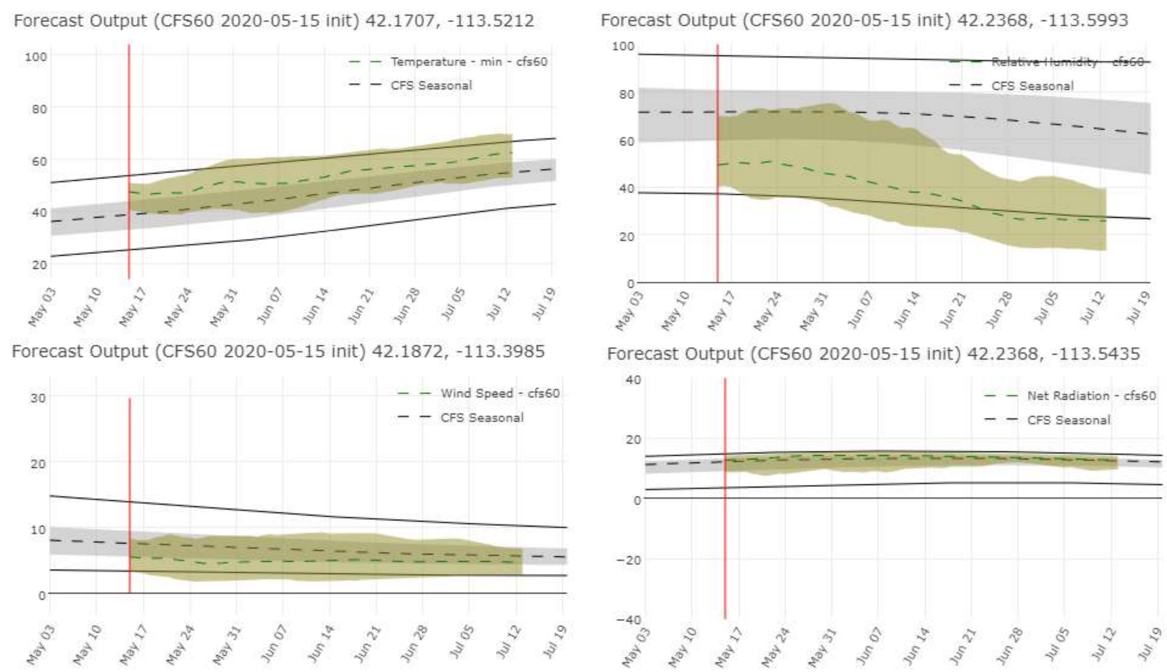


Figure 10. The projected range of forecasted CFS variables for a grid point near Malta, Idaho. Top left: minimum temperature (oF); Top Right; relative humidity (%); wind speed (knots); and net solar radiation (MJ/(m2-day).

An Example 9-Month Outlook

The CFS outlook extends beyond one year. Each day, four forecasts are made at forecast cycles of 00Z, 06Z, 12Z, and 18Z. This results in a very large ensemble of forecasts if one considers that the update cycle of such extended forecasts can be made on a relatively infrequent basis (e.g. weekly or monthly). If CFS outlooks were made weekly using all the forecasts available from the previous week, it would result in 28 forecasts that would extend beyond one year. In the case of these long-range seasonal outlooks, we have condensed the forecasts. The WwET4Cast provides a daily update of the 9-month outlook based on the 28 previous forecasts.

Figure 11 shows the seasonal outlook of ETo for a point in central Nebraska. Note that this point is outside the domain of the AgriMet network, because the intent of the seasonal outlooks is to provide insights into the relative direction of a particular variable — in this case ETo. For this point, there appears to be a tendency toward lower estimates of ETo for the summer months of 2020. Figure 12 shows the seasonal outlook for the CFS grid point near the Malta AgriMet station, suggesting that the outlook closesly matches the historical climatological average. The figure includes the ETo daily observations showing the seasonal pattern and significant day-to-day variability.

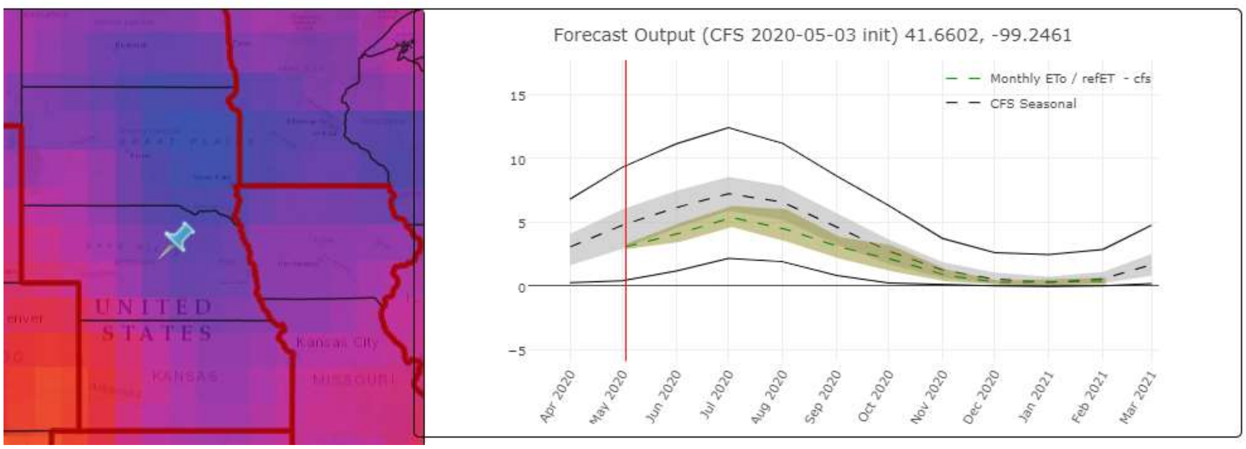


Figure 11. A 12-month seasonal outlook for a point in Nebraska. The gray shaded boundary is the interquartile range of ETo from climate reanalysis, while the dashed dark line is the mean and the solid lines are the maximum and minimum ETo estimates (mm/month). The green shaded area is the interquartile range of the outlook, with the dashed green line as the mean of the outlook.

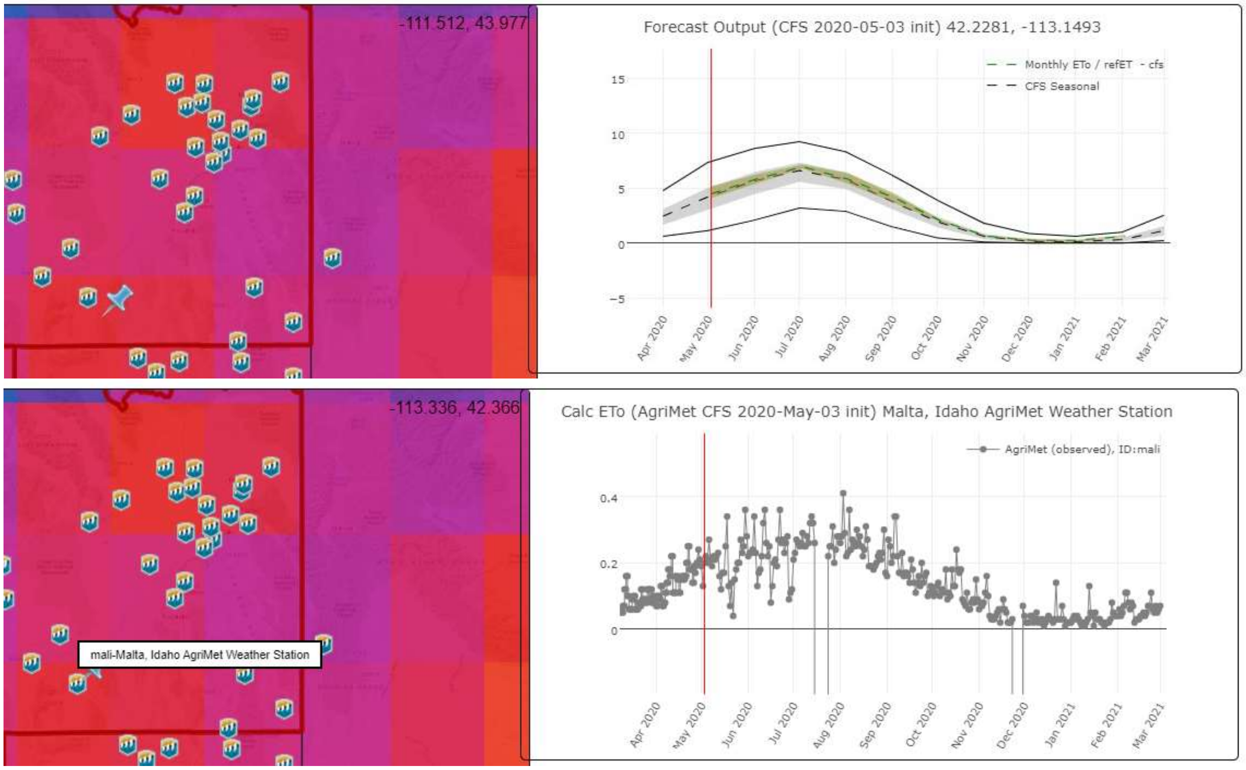


Figure 12. The top figure shows the seasonal outlook for the CFS grid point that corresponds to the Malta site, while the lower figure is the observed, daily ETo time series for Malta from the AgriMet archive.

Forecast Verification

Verification of meteorological forecasts is a critical step in determining the value of the forecast, allowing the user to identify strengths and weaknesses of a forecast system. Issuing a forecast without its verification implies that the quality and value of the forecast are not important, thus verification is a critical ingredient of forecasts, and even more so for sub-seasonal to seasonal forecasts (Mason 2012). The skill of longer lead time forecasts are not as obvious to users. For example, the presentation of long-range weather forecasts (e.g., 10-16 days) strongly resembles the 2- to 3-day forecasts (e.g., the daily resolution). However, forecast skill deteriorates as the lead time increases, because the structure and confidence relative to the timing of the forecast becomes more uncertain. This phenomenon becomes even more exaggerated as the forecasts extend to the sub-seasonal and seasonal domains. Moving weeks and months away from the forecast initialization changes the scientific content, as the information regarding timing of individual weather events becomes lost in the chaotic nature of the atmosphere (Lorenz 1965). In fact, individual weather events as forecast by the GCM at these longer lead times are not just “blurred” but actually become irrelevant. Apart from a very small number of specific time-scales, sub-seasonal to seasonal forecasts are really more statistical outlooks rather than forecasts. Some of the few exceptions might include the timing of hemispheric-scale waves, such as the Madden-Julian Oscillation or MJO. The MJO is an eastward moving disturbance of clouds, rainfall, winds, and pressure that traverses the planet in the tropics and returns to its initial starting point in 30 to 60 days, on average. Similarly, the seasonal cycle becomes increasingly evident in multi-month outlooks, and at that scale, the slowly evolving anomaly structures tied to El Niño-Southern Oscillations (in many domains, though not all) are one of the key sources for skill. In short, the Subseasonal to Seasonal (S2S) forecasts need to be recognized as forecasts at the shorter end (less than 16 days) which evolve into outlooks toward the longer time-scales. Verification products are necessary to provide guidance on what to look for and what to expect.

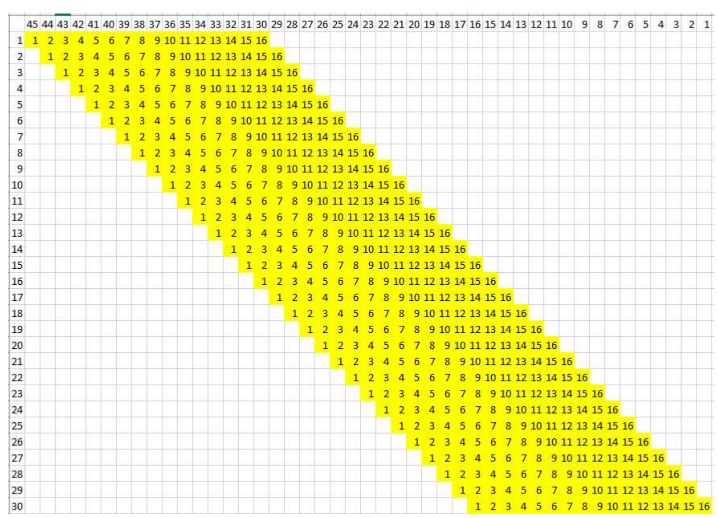
Verification strategy

Because of the range of the forecasting time-scales involved (16-day, 60-day, 9-month), there are fundamental differences in understanding the skill of the forecast products. The main distinction is between "weather-forecasts" and "climate-outlooks," i.e., the GFS-based can be considered as weather forecasts and the CFS-based products can be considered as climate outlooks. A primary difference is that for weather-related forecasts, the high frequency of independent forecasts allows for the use of the previous past few weeks as a sufficient database for evaluating forecast skill. Forecast skill is determined 'dynamically', as the forecasts evolve over time. A user looking at a 16-day forecast can on April 1st, can get a sense of the forecast skill by being provided with information about the skill of the forecast over the previous 16 days.

In contract, for the 60-day to 9-month forecast/outlook range, the past few weeks don't provide enough independent samples (or any at all for the 9-month forecast), thus a different strategy has to be employed for forecast verification. For these long-range outlooks, the skill needs to be assessed over past years. Therefore, we separate the description by GFS-forecast verification for the 1-16-day forecasts from the CFS-based outlooks covering 60-day and 9-months in the next section. The verification of GFS-based forecasts was performed on the station data for use in the irrigation scheduler. The longer 60-day and 9-month outlooks based on CFS outlooks were verified on the gridded data but not for the stations.

GFS-based 1-16-day forecast verification for stations

The verification of the long-range "weather-forecasts" with GFS as the underlying global model is based on the 30 most recent, available daily forecasts and how they performed against what was observed at the stations. The verification can be performed for both AgriMet as well as CIMIS stations, with only AgriMet stations shown here. Because each forecast is 16 days long, the collection of sample forecasts covers the period from 45 days before, when the last forecast has a complete forecast and observation pair throughout the forecast range of 16 days.



The 30 forecasts are first analyzed by comparing their forecasts for each calendar date with the observational record of the corresponding day. Thus all 30 forecast products, each consisting of 15 forecast days (note, the first day is lost, because the 4-member ensemble truncates to the next complete day), are turned into differences by subtracting the observed value at the station from the forecast. These "errors" are then reordered across all 30 forecasts to represent lead times, ranging from 1 to 15 days. This is done so that one can discern how well the forecasts performed as the lead time increased from 1 to 15 days. Different verification statistics can then be calculated for each of these 30 samples, for each lead times.

The following verification statistics are calculated across the 30 daily samples:

- <u>Mean bias:</u> the averaged difference between forecast and observed
- <u>Percent bias:</u> same as bias, but calculated as a percent difference. This is important when looking at skill over longer times because of the zero-bound nature of ET, and thus the differences in skill when comparing the warmer against the cooler periods of the year – or when comparing sites in warmer (lower) or cooler (higher elevation) sites.
- <u>High-count:</u> the percent of forecasts being higher than the observed values to identify possible drifts in the forecast model.
- <u>Root-Mean-Squared Error:</u> Another bias measure but with emphasis on the larger errors.

The collection of samples for the GFS verification could be expanded by looking at the performance over the same period of past years. However, the additional benefit from expanding the sample pool is fairly limited as number of samples is already reasonably high. A good argument could be made for expanding these samples over a few years, though the duration required for the CFS-based forecasts (see below) is certainly not necessary and would not improve the verification quality in a measurable way.

The workflow associated with the 16-day, GFS forecast of ETo was shown as an example of the 16-day forecast for the Malta station in the Results section above. To summarize, the bias-corrected, GFS forecast of ETo generally underestimated the observed ETo for September 6th, 15 days ahead of the August 22 issuing date. The left-side plot of Figure 13 shows the initiating time of the forecast on August 22nd (vertical red line). Qualitatively, model skill did not seem to materialize until around the 2nd of September (right-side plot of Figure 13, which shows the initiating time of the forecast).

15-Day Forecast Issued 22 Aug for 6 Sep **3-day Forecast Issued 3 Sep. for 6 Sep**

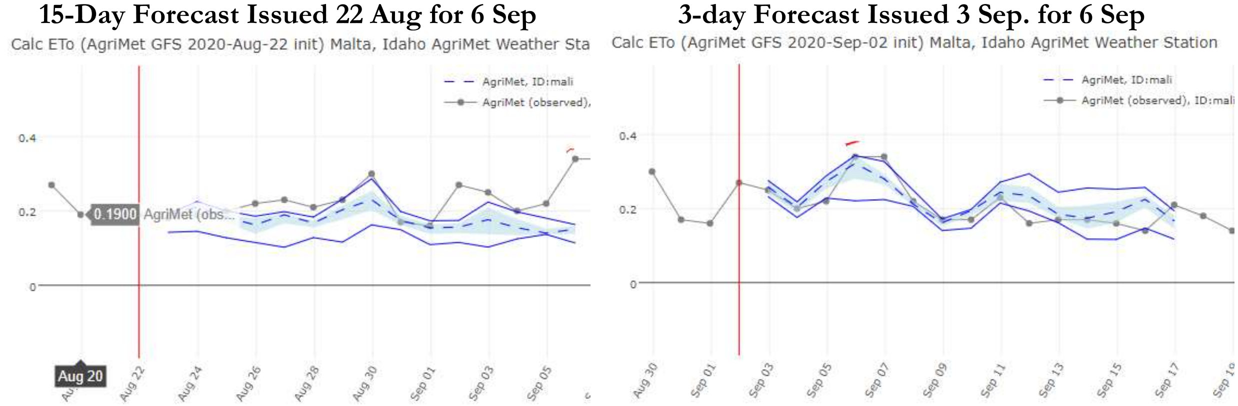


Figure 13. Example of a ETo forecast evolution that targets 6 September 2020 as a day of particular interest in terms of forecast outcomes and performance. Verification of 16-day, ETo forecasts for an

AgriMet forecasted station. The small red mark in both plots is the 6 September 2020 forecasted value (units are inches).

The top plot in Figure 14 is the 16-day GFS-based station forecast for the Malta (mali) station in southeastern Idaho made on 5 May, 2020 (blue) and the observed ETo for the station (light gray) during this period. The forecast shows that it was skillful in forecasting the generally flat trend of ETo over the first 10-days at about 5 mm/day, but missed the upward spike in ETo around 18 May. The bottom graph of Figure 14 is the forecast bias for the previous 30 days for each forecast lead-time in mm/day. The ETo, GFS station-based forecast verification is found by looking back the previous 30-days, and for each lead-time, computing the error between the observed ETo and the model forecast ETo. In addition to Bias, Percent-Bias, Root-Mean-Square-Error (RMSE), and High Counts are included in the forecast verification statistics in the WwET4Cast forecast tool for the GFS-Station forecasts. The High Count is given as the percentage of days (out of 30), where the forecast is above the observation.

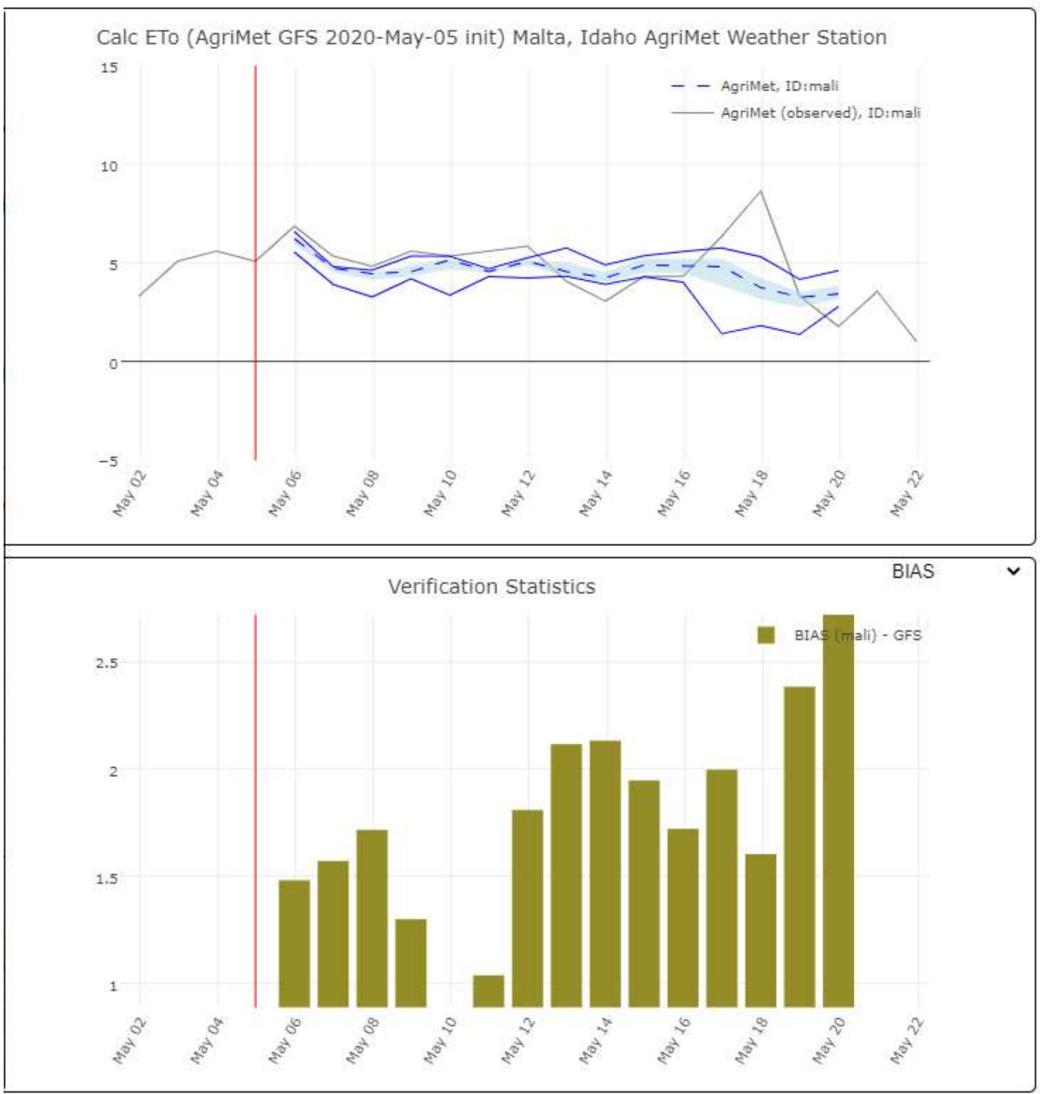


Figure 14. The 16-day forecast of ETo for the Malta (mali(42.4375,-113.4139) station, (top) for the forecast made on May 5th, 2020. The bottom plot is the forecast bias in mm/day, for forecasts made for the previous 30-days.

Figure 15 summaries the forecast and forecast skill for the same Malta (mali) station in southeastern Idaho for a forecast made on the 3rd of September, 2020. The forecast shows an increase in ETo into the first week, which is verified by the observation for the same period, with the forecast staying high relative to the observation to 17 September. The bottom graphs in the summarize the verification statistics derived from forecasts made for the previous 30-days, and shows that the greatest skill of the forecast is in the first week, and the skill it deteriorates into the 2nd week, with bias increasing beyond 10 percent after the first week, which is consistent with the finding summarized in Figure 13. The RMSE error is about 1 mm/day in the first week, and the High Count suggests that the forecasts tend to be about 6% greater in an absolute sense when compared to the station observations

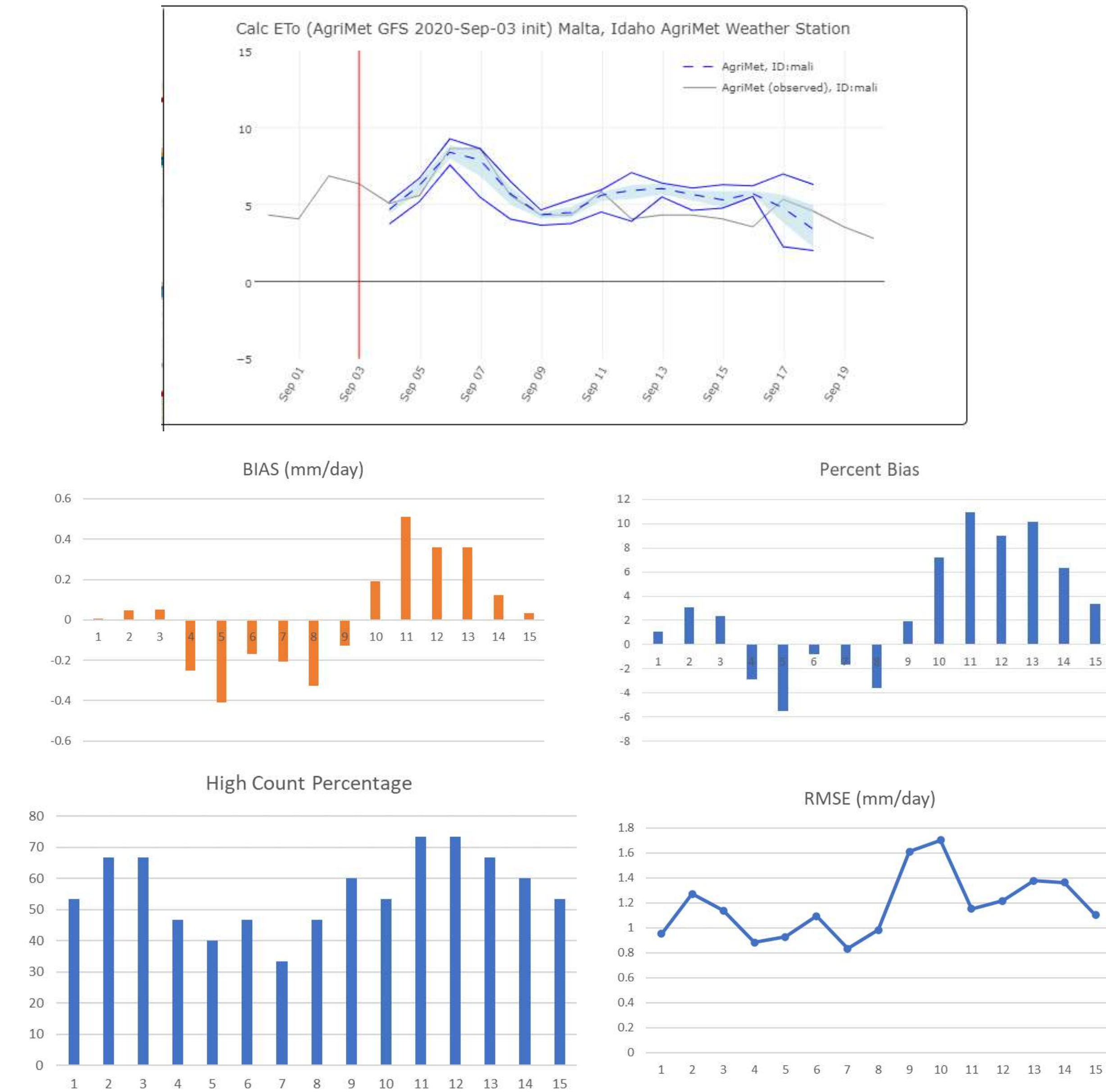


Figure 15. The 16-day forecast of ETo for the Malta (mali (42.4375,-113.4139) station, (top) for the forecast made on Sep. 3rd 2020, and the forecast verification statistics including Bias, Percent-Bias, High

Count percentage, and RMSE. The forecasts have tended to be above the observed ETo (High Count) and biased negative through the first week and positive to the end of this forecast period.

CFS-based 60-day and 9-month verification

The much longer, seasonal forecast realm of CFS-based products do not lend themselves to forecast skill evaluation and verification, based on the previous year's forecast, because seasonal outlooks need to be compared with climatological averages. Therefore, the U.S. seasonal forecasting community has generally used hindcasting period of around thirty years as the period in which to conduct model validation and verification, corresponding to the available hindcast period of roughly 1980 to 2010 (Higgins et al. 2010). The current forecast models (including CFS-version 2) have been rerun in hindcast mode over that period in order to compare forecasts initialized in any month of the year with observations, and to assemble a ~30 sample ensemble. Each of the simulations is 9 months long (or longer), initialized in each month of each year over that ~30-year period. Anytime the forecast model is updated, the hindcasts have to be rerun to provide the verification. The right side of Figure 16 shows the concept of the hindcast ensemble that consists of ~30 runs, each initialized in the same month but a different year to gather a wide diversity of boundary conditions.

To understand the process, it is important to understand that three different CFS-collections are involved in generating useful verification metrics. The workflow to develop the 60-day and 9-month verification statistics are summarized in Figure 16.

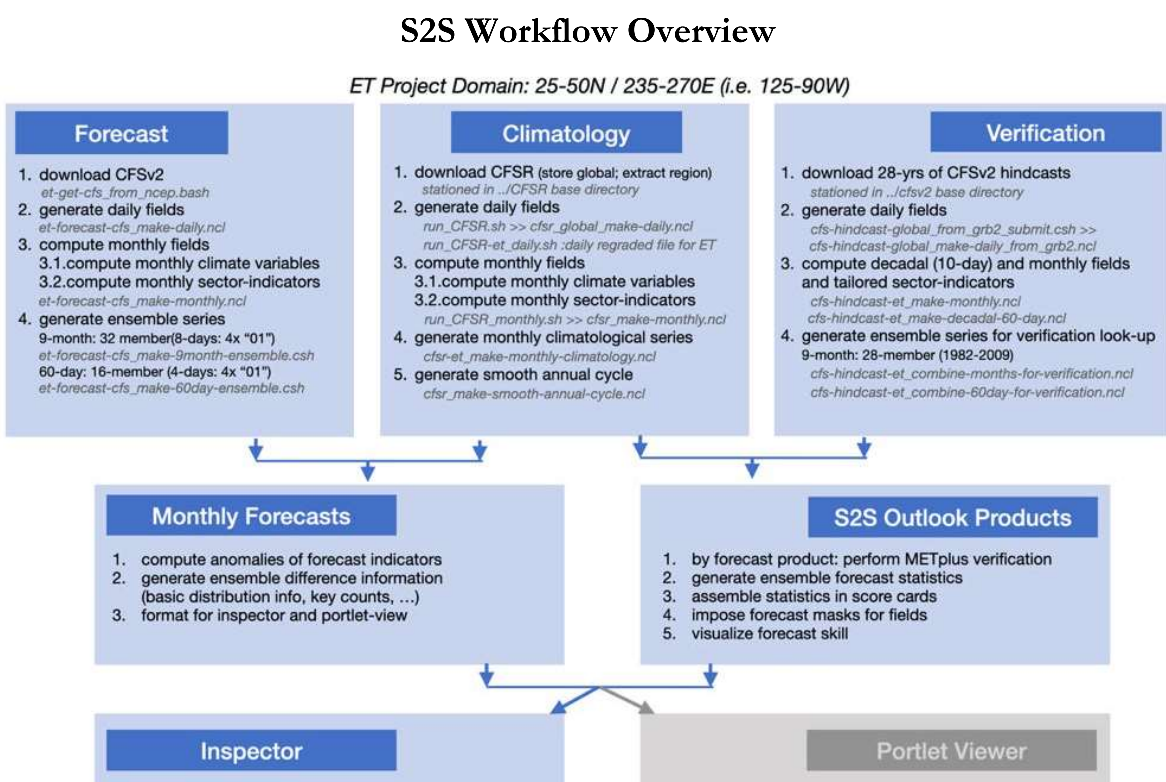


Figure 16. CFS-based 60-day and 9-month forecast workflows using the current operational forecasts, the CFSR-derived "observations" and the 1982-2010 period with hindcasts for verification. S2S is Sub-seasonal-to-Seasonal.

- First, there is the actual, **operational forecast** that is initiated four times per day, each 6 hours apart (top left in Fig). Each of the forecast simulations are provided with 6-hourly output, which is converted into daily products for each meteorological variable. The daily time step is the foundation of all processing because it is the lowest level from which derived products might be computed from (e.g., ETo, etc.). These daily aggregations are then further aggregated into six 10-day "decad" values as well as 9-month forecast products. Note, the decad values are continuous with an individual start and end of period date, while the 9-month forecasts are based on monthly values that follow the calendar months for ease of comparison and aggregation. For a better sampling of the solution "space," the forecast products are aggregated over a multi-day interval. For the 60-day products, the 16 members over the past 4 days are combined, while for the 9-month seasonal outlook, up to 32 members over the past 8 days are combined to better describe the forecast distribution. Aggregation makes sense because the "timing" of individual events is neither relevant nor resolved in the aggregated products. These are presented in WwET4Cast inspector web-browser.
- Second, the **"observational" record** for assessing the hindcasts is drawn from a **continuous reanalysis-**like run of the CFS. This "CFSR" simulation (CFSR, Saha et al. 2010) has been run in 6-h segments, each initial condition improved with observational data using a data-assimilation step (middle in Figure). The resulting single time series over the 1982-2010 period then serves as the ground-truthing for the different hindcasts. Additionally, this 30-yr interval allows us to compute the climatological range through the year. This byproduct is used to compute anomalies, which offer a more refined way for the verification as the sign of the anomaly is often more important than the absolute value of a particular climate variable.
- Third, the **hindcasts** are assembled for one simulation for each of the same calendar month over the period of 1982-2010 (top right in Fig). These hindcasts are processed exactly the same way as the operational forecasts, but compiled into a ~30-member ensemble. Each ensemble member is then compared to the corresponding observational period to generate differences (see above). This difference is either used as absolute value or in form of anomalies after first removing the climatological mean. Based on these collections of hindcasts, the verification statistics can be computed.

The WwET4Cast inspector web-browser includes the suite for verification statistics, derived from the 28 samples of the 60-day and 9-month outlooks that include Root-Mean-Squared Error (RMSE), absolute bias (based on the unit of the variable), percent bias (particularly useful for zero-based variables, such as precipitation or ETo), as well as Anomaly-Correlation Coefficient (ACC). The ACC removes the seasonal influence and if the ACC equals one, then the forecast is perfectly correlated to the observation. An ACC value of minus one means they are negatively correlated, while a value of zero suggests there is no correlation between the observation and the outlook, Here, f and o are the forecasts for the 30-members and for each calendar month

$$ACC = \frac{\sum_{i=1}^{n}(f_i - \bar{f})(o_i - \bar{o})}{\sqrt{\sum_{i=1}^{n}(f_i - f)^2 \sum_{i=1}^{n}(o_i - \bar{o})^2}}. \quad \text{(Eqn 2.)}$$

For the 60-day and 9-month outlooks, these are pre-computed verification statistics that are available as lookup tables for each month of the year. The inspector presents the forecast ensemble information superimposed on the climatological background (smooth shading of the historical range) through selected distributional information, based on percentiles across the respective ensembles. But these quantities could be changed to reflect specific bounds, such as terciles or other characteristics. Separately, in the form of 10-day (decad) or monthly values, the verification statistics for different lead times are given in bar-chart format. The visualization in Figure 17 illustrates the evolution of the forecast quality that could be expected, given the reference period of the hindcasts, 1982-2010.

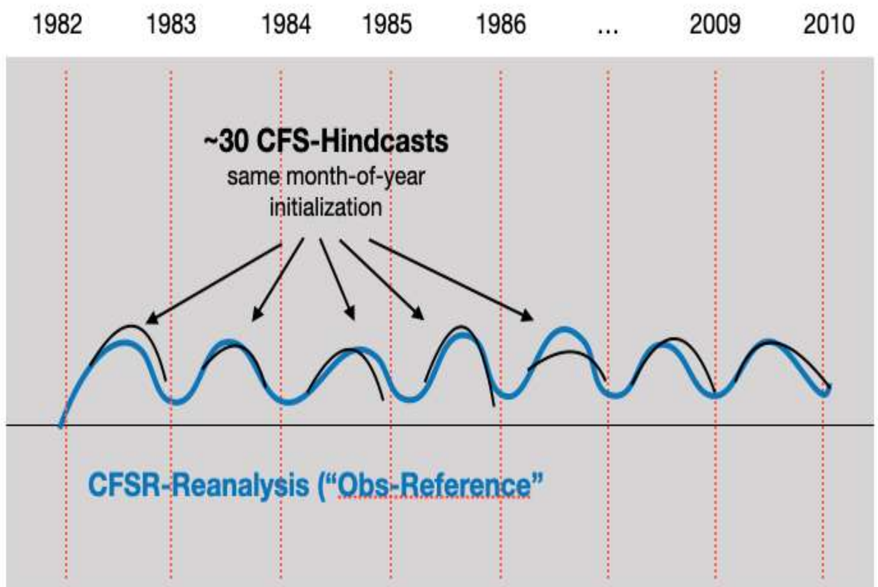


Figure 17. Conceptualization of the seasonal hindcast using the period of 1982-2010 for repeated opportunities

Figure 18 shows the verification of the 60-day outlooks for ETo and minimum temperature for a grid point in southeastern Idaho. Generally, the ETo outlook for this point matches the climatological average, suggesting that the extended range outlook is not more informative that an assumption of climatology. The minimum temperature outlook for this point suggests temperatures slightly above the average, and the anomaly correlation coefficient for this meteorological variable is higher than the ACC shown for the ETo variable. While the temperature outlook is slightly higher, the outlook for other meteorological variables that impact ETo show a different outlook trend. Wind speed, for example, was forecast to be, on average, below the climatological average at this point on September 2nd for the following 60-days, so it is perhaps compensating for the higher temperature values (see Table 1 to identify the relative contribution of each meteorological variable to the ETo estimate and note that we are not showing the plot's wind speed here).

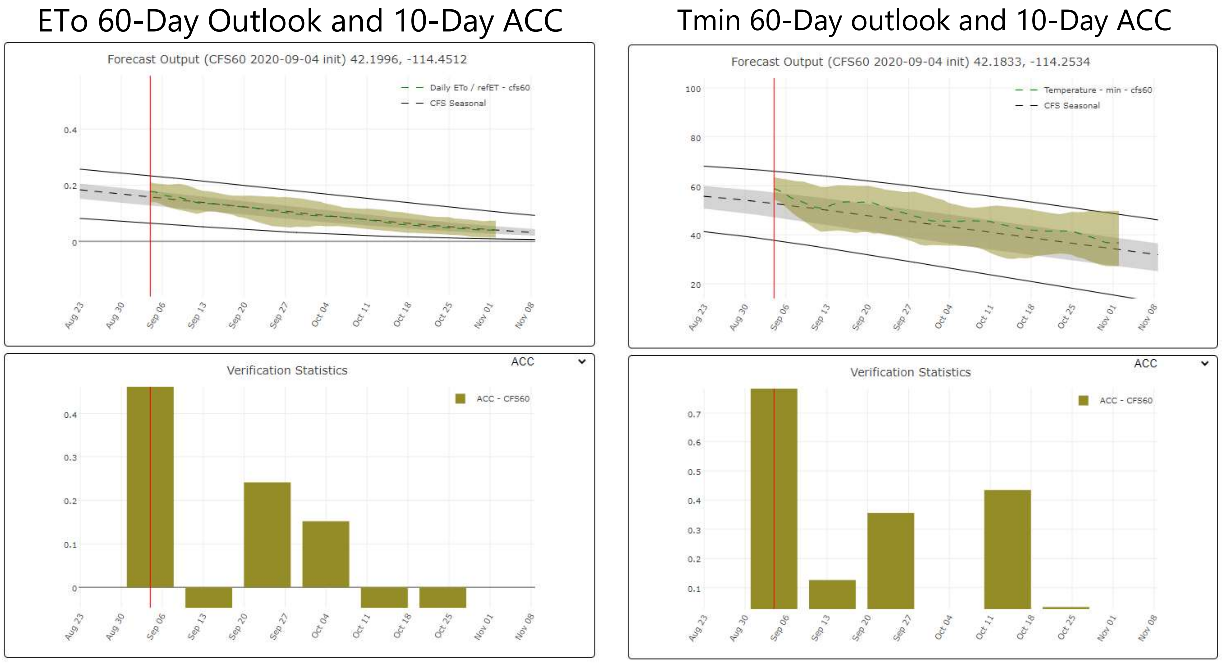


Figure 18. The 60-day outlook for a forecast point in south central Idaho, showing the outlook for ETo (left top) and minimum temperature (top right). The outlook for ETo is essentially climatology, while the outlook for minimum temperature is above normal. The Anomaly Correlation Coefficient (ACC) for ETo out 10-days is not much more skillful than climatology with values below 0.5, while the ACC of 0.7 out 10-days (lower-right) for the minimum temperature field suggests more skill for this variable.

Conclusions

This project demonstrated the development and implementation of a sub-seasonal to seasonal forecasting system of reference evapotranspiration (ETo) for two large meteorological observing networks in the western United States, Reclamation's AgriMet network and DWR's CIMIS network. Using the operational forecasts made available from the NOAA's Global Forecast System (GFS) and Climate Forecast System (CFS) models, 16-day, 60-day, and 9-month forecasts and outlooks were generated operationally on a daily basis. A web-browser-based graphical user interface was developed that can be used to explore the forecasts for the individual agro-meteorological stations and/or a select a location at grid points across the western U.S. In addition to the browser-based tool, API capability was added to the system to allow outside users the ability to extract the forecast data itself, thus bypassing the need to use the web-browser directly. The project team collaborated with Dr. Troy Peters of Washington State University, who developed a mobile-phone based application interface for field-scale irrigation scheduling, allowing the integration of the forecasts into his tools. With the provision of the ETo forecasts, the irrigation scheduler application can be used to give timing and amount of irrigation out 16-days in advance for individual weather stations of interest that are members of the meteorological networks.

In addition to the station-based forecasts, the 60-day and 9-month outlooks of ETo and the other meteorological variables can be explored across the domain of the western United States using either the web-based browser interface or through queries using the API. An outside user could create python or similar type of scripts that use tools such as "wget" or "curl" to download the data for their particular application or need. The outlooks are placed within the context of the historically observed range of particular variables (ETo, temperature, humidity, solar radiation and wind speed), to give the user a sense of whether or not the outlook deviates significantly from the historical range.

In addition to the absolute forecast and outlook values for the stations and the grid, the WwET4Cast provides forecast verification statistics to give the user a sense of the expected skill of the forecast. These skill metrics include bias, percent bias, the anomaly correlation coefficient (ACC), and the root-mean-square error (RMSE).

Recommendations and Next Steps

A few recommendations and next steps are listed below.

- The data server should be moved to the cloud or housed on a Reclamation server.
- A set of use cases could be developed and customized for users such as Dr. Troy Peters, where forecast outputs could be provided to his irrigation scheduling tool and assessed in terms of the value added of the forecast to the irrigation decision.
- Additional observational networks could be added to the data server and included in the station-based forecasts.
- Generate a station-based, bias-corrected forecast for the gridded field, allowing for sub-grid representation of the forecasts at any point throughout the domain.
- Conditional Assessment - The seasonal outlooks at 60-day and 9-months suggested marginal skill. However, it would be valuable to explore the conditional skill of these outlooks for a particular meteorological conditions (i.e. is there more skill in ENSO years).
- Currently, the bias correction procedures are deployed at the station level only. This means that ETo forecasts made for points in the domain of interest (i.e. the western U.S.) that do not correspond to individual stations are based on the raw GCM model outputs. A set of procedures could be introduced that develops gridded meteorological fields that are bias corrected against station information allowing for a more accurate ETo forecast anywhere in the domain.

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A1. The Web-Based Forecast Inspector- User Guide

This appendix serves as an overview of the West Wide ETo Forecast Network Inspector (WwET4Cast) by introducing its core elements and outlining how it is deployed on the NCAR web-server. The functionality as of January 2021 is to be regarded as a development version with further optimizations to be considered and ultimate deployment on a server outside of NCAR. WwET4Cast is a web-based tool to assist Reclamation in informing its users about likely Sub-Seasonal to Seasonal water-demand outlooks. WwET4Cast is intended to provide quick insight into different forecasts / outlook fields, on a range of timescales. The intent is to provide daily to monthly-level insight into a small number of pre-selected forecast fields, chiefly the ETo forecasts, and to augment the map-based fields with useful additional information to provide context for interpretation. However, WwET4Cast is not intended to be the only tool for exploring the ETo forecasts or the primary interface for practitioners that want to make use of the actual forecast data. There is an API that allows users to automate the extraction of the forecast data for their use. The browser interface for the coordinators of the user outreach to monitor whether the underlying data infrastructure is operating properly, and to identify possible important weather situations that warrant special attention.

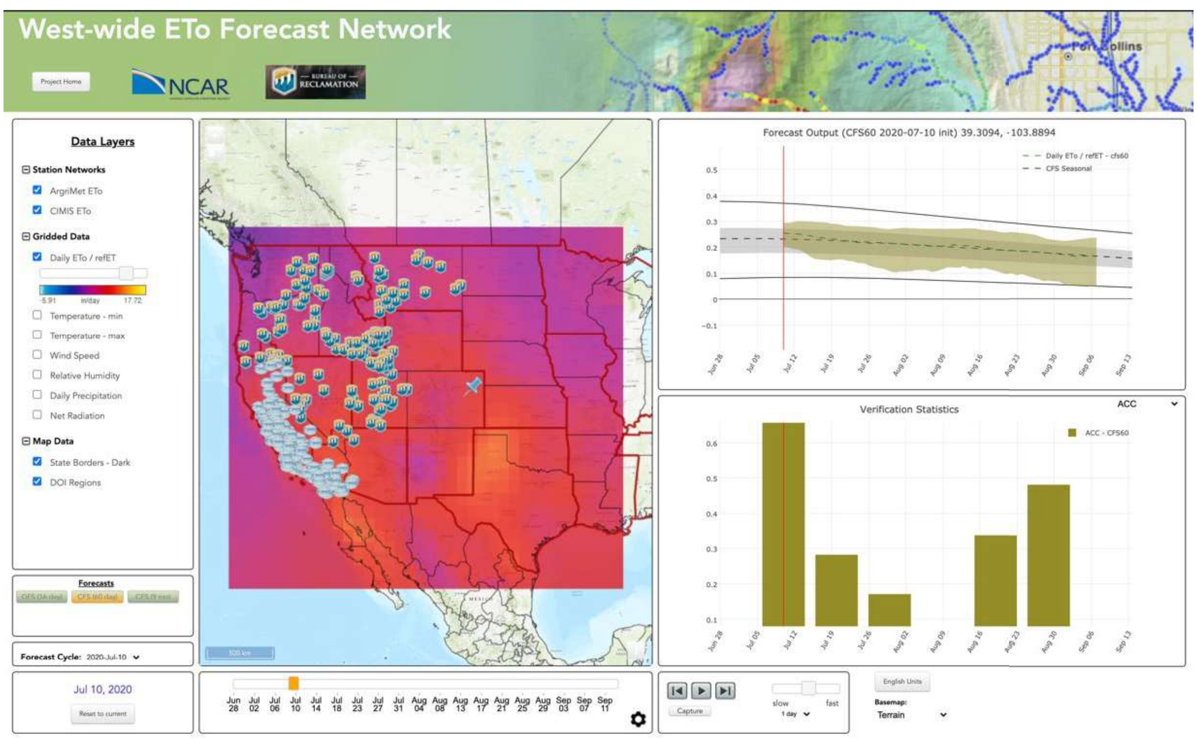

Figure A19. Screenshot of the West-wide ETo Forecast Network Inspector. The view is split into four sections with run and data selection on the left, a main visualization window with a zoomable map in the middle, special insight into point and climatological and verification data on the right, as well as time selector tools at the bottom.

WwET4Cast offers links to the archives of completed forecasts from both GFS for the sub-seasonal 16-day forecasts and the CFS-driven experiments for seasonal time scales. The model output provided in the main window is augmented by secondary insight into either point-data time series or the broader context provided in the additional windows on the right side. A temporal slider at the bottom allows users to select different time-intervals from the simulations.

Objectives of WwET4Cast

WwET4Cast is not intended to provide all tools for all possible questions. It provides access to the basic and most used data fields. Its standardized structure allows for easy changes and updates during the development phase, but it should then be operated under constant settings. The preparation of model data (e.g., the GFS and CFS post-processing steps) generates a single file containing daily time series of both long-range weather (up to 16 days) and seasonal climate outlooks (up to 9 months). The post-processing tool, however, is more flexible and can be extended to generate more time series intended for analysis.

Technical Background User Interface

The WwET4Cast application is a web-based viewer for rapidly accessing and inspecting daily, 10-day, and monthly operational forecasts of ETo and other meteorological variables for the western United States based on forecasts from the NOAA GFS and CFS. Its design follows a client-server architecture. The client is written primarily in Javascript and thus can run inside any standard web browser (note: Firefox or Chrome are recommended for performance and robustness). The server is the java-based open-source THREDDs server, which provides image tiles and time-series data to be rendered in the client. THREDDs is the conduit to the netCDF files that are generated through post-processing of the model runs and global-model input data. The real-time workflow control environment and web server are implemented on NCAR-RAL servers[10]. The workflow environment is based on the Open Source ecFlow package, which enables users to run a large number of programs with dependencies on each other and on time; and submits jobs generated from scripts and receives acknowledgement from them when their status changes (e.g. active, completed, or aborted) and when they send events for other process to act upon. ecFlow stores information on how tasks are connected to each other and is able to submit tasks dependent on actions and triggers (e.g. a station forecast of ETo cannot be made until the forecast model has been completed and the data are available).

It can be configured to be accessible only inside an operational center's firewall; it can be placed on an exposed server using password-protected access; or it can be made fully publicly accessible. Once in place, it is an operational tool designed to grow with the expanding collection of simulations. Operational forecast data will be available in near real time, and the user is able to select from the current or previously-generated forecasts. Additionally, users will be able to submit developmental forecast runs, and they can be selected by name in the tool. Matching GFS (16-Day) and CFS (60-day and 9-month) data are available for viewing as well for previously run forecast cycles.

[10] This server was running as of 17 Apr 2021.

The user can select and display gridded data overlaid on a "google maps"-style interactive map with pan and zoom available. The map can also be clicked at any grid point to see the evolution of GFS or CFS data in a time-series plot (top window on right side of screen). Plots can be viewed in the WwET4Cast tool, or interactively in a pop-out window. The pop out is activated by double-clicking on the embedded windows, which brings up an interactive plot that is based on an open source python plotly toolset[11].

WwET4Cast details

Currently, the ETo web-based forecasting tool is deployed on a server at NCAR and can be accessed here, https://hydro.rap.ucar.edu/HydroInspector/WW_ETfcst/. It requires a user login, which can be supplied by request by emailing NCAR at yates@ucar.edu. Below we describe the function of the service.

User Interface- The inspector contains many connected elements. It is useful to work your way through by following the sequence proposed here:

1. Forecast Model Selector
2. Forecast Selector
3. Station Network Selector
4. Variable Selector
5. Map Viewer (zoom/ click)
6. Timeseries Viewer
7. Verification Viewer
8. Time Selector Lever
9. Time Operator / Monitor
10. Basemap Selection
11. Map Element Selector

1 Forecast Model Selector ("Forecasts")

The first selection relates to the type of forecast, which is either a 16-day long-range weather forecast using NOAA's Global Forecast System (GFS), or the sub-seasonal to seasonal climate outlook driven by the Climate Forecast System (CFS) going out 60 days or 9 months.

Note, the West-wide ETo Forecast Network Inspector automatically handles the time variable, and the distinction between the different model run categories is done through the directory tree structure and file naming conventions.

- `GFS (16 day):  1 to 16-day`
- `CFS (60-day):  aggregated in 6 separate 10-day segments`
- `CFS (9-month): aggregated monthly for 9 forecast months`

[11] https://plotly.com/python/

2 Forecast Selector ("Forecast Cycle")

For each forecast category (selected under 1), the Inspector will automatically retrieve a list of available forecast datasets that can be viewed. The detailed influence on the directory tree as well as file naming and other conventions is listed below:

- *GFS*:
  - forecast of 1-16-days
  - using NOAA-GFS 16-day forecasts
  - ensemble of currently 4 daily runs
  - model *init-time*: day of launch
  - individual runs stored in directory:

    `e.g. ./gfs/2020/202007/20200710/gfs4…`
- *CFS (60-day):*
  - forecast of 1-60-days
  - using NOAA-CFS 9 months forecasts
  - ensemble of currently up to 16 individual runs over the past 4 days
  - model *init-time*: day of latest forecast cycle
  - run stored in directory:

    `e.g.: ./cfs/2020/202007/20200710/cfs2…`
- *CFS (9-month):*
  - forecast of 1-9-months
  - using NOAA-CFS 9-months forecasts
  - ensemble of currently up to 32 individual runs over the past 8 days
  - model *init-time*: day of latest forecast cycle
  - run stored in directory:

    `e.g.: ./cfs/2020/202007/20200710/cfs2…`

Other data prepared but not intended for direct view in Inspector:

- **CFSR operational reanalysis** in past (1982-present, ens, size: 1 per month or 1 per 10-day interval)
- **CFS hindcast seasonal ensemble** (ens. size: ~30 / month).

3 Station Network Selector

The station network selector is the place to activate the icons representing different stations on the adjacent map display. Individual networks can be selected or turned off. Currently, the included networks are AgriMet and CIMIS. For each of the networks, the selected variable (see (4)) will then be displayed in the timeseries viewer.

- `AgriMet ETo`
- `CIMIS ETo`

4 Variable Selector

The variable selector provides access to standardized variable lists assembled during post-processing. Only a limited number of 2-dimensional fields are available as the goal of the inspector is to quickly provide insight into the main outcomes of the forecasts and not to serve as an in-depth analysis tool. First in the list, of course, is the forecast of ETo. Below each selected variable there is a color bar that can be double clicked for adjustment. A slider controls the transparency level.

A few fields are only available:

- **Daily ETo / ref-ET**
- **Daily Minimum Temperature**
- **Daily Maximum Temperature**
- **Wind Speed**
- **Relative Humidity**
- **Daily Precipitation**
- **Net Radiation**

5 Map Viewer

The map window can display one or more variables in color contour or vector map form. The map itself is zoomable from high-resolution local to global scales, though the data displayed is limited here to the domain of analysis. Depending on scales, the data detail adjust automatically (particularly for wind vectors). The base-map draws from the OpenStreetMap consortium data and can be switched between light background map to satellite image.

The map is "clickable" to offer access to single points in the gridded fields. This selection then populates the two auxiliary graphs to the right. If activated, individual stations from the available stations networks can also be selected.

- Zoomable map (global to local)
- Turn on "State Borders" and/or "Reclamation Regions" under Map Data for clearer outline
- Color-contour field through variable selection
- Wind field shown with vectors
- Clickable for location selection

4 Time-series Viewer

The map offers an interactive access to point locations based on gridded data or stations. By clicking on a place on the map where a climate field is shown, the upper-right auxiliary plot then shows the full time series of that variable for that location.

- Access to location-specific time series
- Double-click the graph to open it in a separate window

7 Verification Viewer

To illustrate the confidence in the current forecast, verification is done comparing forecasts done with the same model for the same month of year against reanalysis data of what actually then happened. The verification results are quantifying in different ways how the forecasts systematically reproduced or failed to predict the field of interest. The forecasts need to have been performed with the same model: At the global model level, these are "hindcasts" using the CFS-version 2 model compared to CFSR, the CFS-based reanalysis.

- Currently four different verification statistics are implemented: Anomaly Correlation Coefficient (ACC), bias, percent bias, Root-Mean-Squared-Error (RMSE)

8 Time Selector Lever

The model output is stored as long time series and this interface element offers the user quick access to different time slices. The content of the available time series loads automatically with the selection of the model run (2). The orange lever can be moved with the mouse to any time over the available time series, causing the map to update. As the lever is placed on a new day, the vertical "current" time indicators in the two right-hand-side auxiliary plots are not updated, just the map.

9 Time Operator & Monitor

An additional navigation tool for advancing the visualized time slice is by using the Time Operator with its "play" and "advance" buttons (see Figure with circle on the right). By clicking a direction of advancement, and then follow up with a click on the play button, the map visualization with update and automatically update the frames. The speed selector to the right allows the user to change the speed of change. The Time Monitor, on the far bottom left of this window, keeps a detailed view of the selected date and time.

10 Basemap Selection

Because changing the basemap is not a frequent operation, the selector tab has been moved to the far lower right. It allows switching between different standard base maps in the map window, including the option to turn on Satellite Image.

11 Map Data

To get an overview about availability of data along the time series, the Data Availability Window is useful to illustrate how synchronous data from the global driving model is available

API Queries and Data Return

As mentioned, a primary goal of this project is to add value to the station observations by providing forecasts based on those provided by the NOAA GFS and CFS forecast models. While direct access to these forecasts via the web-based user interface is useful, more advanced users might want rapid access to the actual forecast data in a convenient and automatable manner. This type of functionality is often achieved by coding an application programming interface (API) that allows the extraction of values by formatting the URL string in a manner that allows access to the forecasts, allowing for the user to bypass the web-based interface. This allows the use of tools such as curl, which is a command-line utility for transferring data from or to a server designed to work without user interaction. With curl, you can download or upload data using one of the supported protocols including HTTP, HTTPS, SCP, SFTP, and FTP. Another popular utility for retrieving content from web servers is "wget," whose name derives from the World Wide Web and also supports downloading via HTTP, HTTPS, and FTP.

Below are three example URLs for retrieving station and gridded point data from the WwET4Cast server. Note that absolute forecasts of the station ETo are only being made for the 16-day, GFS forecasts. Because the longer range forecasts from the CFS that go out 60 days and 9 months are generally presented as anomalies relative to the historic forecasts, it is not considered that absolute forecasts for these seasonal forecasts are that useful.

Parameters needed for retrieving observational data, GFS forecasts, and CFS forecasts for individual stations for the GFS forecasts. Note that the *%20* in the string that formats the date is used to encode a space character in the URL expression:

Note that the station data download are only for the ETo estimated values and in fact, since these data are available from the Agrimet and CIMIS sites, we recommend retrieving the data from there. For the ETo extraction, a Station's data can be downloaded as:

`https://hydro.rap.ucar.edu/HydroInspector/WW_ETfcst/servlet/servlet.php?requestType=getTimeSeriesData&productId=agrimet&id=golw&start=2020-12-03%2019:12:00&end=2020-12-24%2014:24:00&model=gfs`

ProductId= agrimet or cimis (station network)
Start= YYYY-MM-DD (start day for which data are to be returned)
End = YYYY-MM-DD (end ay for which data are to be returned)
id = station id (agrimet or cimis)
forecastCycle= YYYMMDDHH (year, month, day, and hour of the particular forecast cycle. The available forecast cycle times are 00, 06, 12, and 18 Z.
Model=gfs or cfs (the Global Forecast System Model and the Climate Forecast System Model. This request requires this field since it is returning the model forecast)
latitude = latitude of grid point
longitude = longitude of grid point

For the climate model forecasts, there are data for several meteorological variables available via the web-based API for both the GFS and CFS Forecasts. The variable name and the abbreviation that should be used for extraction from the API include:

```
ProductId Options
refevt: Reference Evapotranspiration (mm)
tasmax: Maximum daily temperature (oC)
tasmin: Minimum daily temperature (oC)
windspeed: Daily average windspeed (m/s)
rhum: Relative Humidity (%)
pr: precipitation (mm)
ps: Surface pressure (mbar)
netrad: Net radaiation (w/m2)
```

This one returns 60-day CFS data at a lat/lon point.

`https://hydro.rap.ucar.edu/HydroInspector/WW_ETfcst/servlet/servlet.php?requestType=getTimeSeriesData&productId=etfcst&variable=refevt&start=2020-12-03%2019:00:00&end=2020-12-24%2014:24:00&model=cfs60&forecastCycle=2020120700&latitude=43.85&longitude=-118.0`

This one returns forecast data for the 9-month forecast, at a lat-lon point: (Note the 'forecastCycle' parameter) https://hydro.rap.ucar.edu/HydroInspector/WW_ETfcst/servlet/servlet.php?requestType=getTimeSeriesData&productId=etfcst&variable=refevt&start=2021-01-02%2004:00:00&end=2021-12-30%2021:36:00&model=cfs&forecastCycle=2021022700&latitude=45.3&longitude=-122.8

Note that this call returns an agrimet station forecast for a particular forecast cycle (available field for returning station estimates is only ETo)

https://hydro.rap.ucar.edu/HydroInspector/WW_ETfcst/servlet/servlet.php?requestType=getTimeSeriesData&productId=agrimet&id=fogo&start=2021-02-27%2000:00:00&end=2021-03-16%2014:24:00&forecastCycle=2021022700&model=gfs

Data Sets that Support the Final Report

There are two primarily observational datasets used in this project including 1) the AgriMet data and 2) the CIMIS data; and there are two Global Climate Model (GCM) forecast models being used including the Global Forecast System (GFS) and the Climate Forecast System (CFS) models.

Data Description: Since this is a data intensive project, the attributes of the data are presented primarily in the body of the report. The GFS data reference is NCEI DSI 6182, NCDC-GFS_FORECAST, gov.noaa.ncdc:C00634; while the CFS data reference is NCEI DSI 2001_01, gov.noaa.class:NCDC-CFSV2_FORECAST, gov.noaa.ncdc:C00877

Approximate total size of all files: The data archive as of 1 March 2021 is approximately 8 GB and includes a copy of the AgriMet and CIMIS station data (400 MB); and the forecast data (7.6 GB).