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Better Coverage of Arizona's Weather and Climate
Gridded Datasets of Daily Surface Meteorological Variables

Jeremy Weiss and Michael Crimmins

Many areas that use agricultural and environmental science for management and planning – ecosystem conservation, crop and livestock systems, water resources, forestry and wildland fire management, urban horticulture – often need historical records of daily weather for activities that range from modeling forage production to determining the frequency of freezing temperatures or heavy rainfall. In the past, such applications primarily have used station-based observations of meteorological variables like temperature and precipitation. However, weather stations are sparsely and irregularly located throughout Arizona, and due to the highly variable terrain across the state (Figure 1), information recorded at these sites may not represent meteorological conditions at distant, non-instrumented locations or over broad areas. This issue, along with others related to quality, length, and completeness of station records, can hinder the use of weather and climate data for agricultural and natural resources applications.

In response to an increasing demand for spatially and temporally complete meteorological data as well as the potential constraints of station-based records, the number of gridded daily surface weather datasets is expanding. This bulletin reviews a current suite of these datasets, particularly those that integrate both atmospheric and topographic information in order to better model temperature and precipitation on relatively fine spatial scales, and is intended for readers with knowledge of weather, climate, and geospatial data. In addition to addressing how these datasets are developed and what their spatial domain and resolution, record length, and variables are, this bulletin also summarizes where and how to access these datasets, as well as the general suitability of these datasets for different uses.

Figure 1. With the highly variable terrain across Arizona, weather and climate can change dramatically over relatively short distances. Photo credit: Jeremy Weiss

Topography, Weather, and Climate

As is typical across much of the western U.S., the complex terrain in Arizona can strongly influence weather and climate at a location through a number of factors (Daly 2006). For example, pronounced differences in average temperature and precipitation occur along altitudinal gradients, with cooler temperatures and greater precipitation typically found at higher elevations. Topography also determines windward and leeward sides of mountain ranges that influence where moist air is lifted and precipitation falls, aspect – the cardinal direction a slope faces – that modulates solar radiation and temperature, and valleys that are susceptible to cold-air drainage and temperature inversions during winter. Integration of such topographic factors with meteorological station data is critical for generating gridded datasets that more accurately represent daily surface weather at relatively local scales across a region.

Currently Available Gridded Datasets of Daily Surface Weather Variables

The concept behind gridded datasets of daily surface weather that integrate both meteorological station data and topographic factors – gridded daily topoclimatic datasets – is to combine point-based observations of meteorological variables like temperature and precipitation with information derived from digital elevation models, or DEMs (Figure 2), and statistically interpolate values of such variables to a spatially complete and uniform grid of relatively fine scale. More

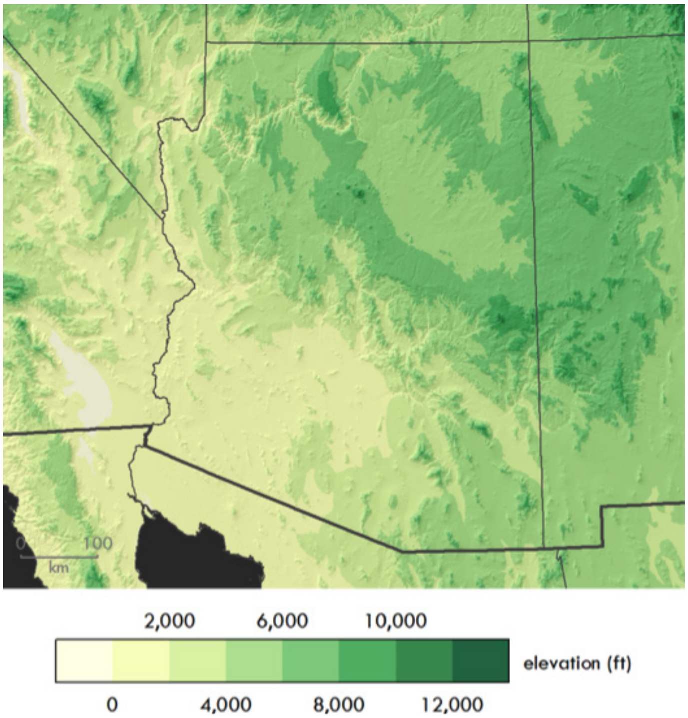

Figure 2. Digital elevation models, or DEMs, provide information on several topographic features that influence weather and climate, including elevation, aspect, and slope. The digital elevation model shown here is one of the inputs used to generate the Topography Weather (TopoWx) dataset, as described later in this bulletin. These elevation data are available at http://www.ntsg.umt.edu/project/TopoWx.

recently, this type of an approach has begun incorporating additional input data from satellites and radar estimates in order to improve the accuracy of temperature and precipitation grids, respectively.

There are five major gridded daily topoclimatic datasets currently available. The development, record length, frequency of updates, spatial domain and resolution, variables, and climatologies of each are described below (Table 1).

Daymet

Initially developed as input to broad-scale ecological and hydrological models, the Daymet dataset is based on a diverse set of observed temperature and precipitation data that are processed through an inverse-distance weighting algorithm and smoothing filter (Thornton et al. 1997; http://daymet.ornl.gov/overview.html). The process also incorporates techniques that account for relationships between elevation and both temperature and precipitation in order to improve prediction of these variables at sites with no observations. In addition to minimum temperature, maximum temperature, precipitation occurrence, and precipitation amount, the Daymet dataset includes modelled surfaces of humidity, solar radiation, snow water equivalent, and day length (Table 1). Humidity, given in terms of water vapor pressure, is based on the assumption that minimum temperature reasonably estimates dew point temperature and is generated as a

Table 1. Attribute summary of gridded daily topoclimatic datasets that are currently available and reviewed in this bulletin.

Dataset	Record length	Update frequency	Spatial domain	Horizontal resolution	Variables	Available climatologies	Reference
Daymet	1980-latest complete calendar year	annually	contiguous U.S., Mexico, and Canada (south of 52°N)	1km x 1km	minimum temperature maximum temperature precipitation occurrence precipitation amount humidity solar radiation snow water equivalent day length	individual monthly average individual annual average	Thornton et al. (1997)
PRISM	1981-present	sub-weekly, but data remain provisional for several months	contiguous U.S.	4km x 4km	minimum temperature maximum temperature precipitation total (rain plus melted snow)	individual monthly average 30-year monthly average (1981-2010) individual annual average 30-year annual average (1981-2010)	Daly et al. (2002)

Dataset	Record length	Update frequency	Spatial domain	Horizontal resolution	Variables	Available climatologies	Reference
UofI METDATA	1979-present	sub-weekly	contiguous U.S.	4km x 4km	minimum temperature maximum temperature precipitation amount precipitation duration relative humidity specific humidity surface downward shortwave radiation wind velocity	n/a	Abatzoglou (2011)
TopoWx	1948-2012	annually	contiguous U.S.	~800m x ~800m	minimum temperature maximum temperature	individual monthly average 30-year monthly average (1981-2010)	Oyler et al. (2014)
AHPS	2005-present	daily, but data are subject to change over subsequent days	contiguous U.S. and Puerto Rico	4km x 4km	precipitation total	n/a	Lawrence et al. (2003)

function of both minimum and average daylight temperature. Sun-slope geometry, diurnal temperature range, and snow water equivalent determine solar radiation. Daily Daymet data are available from 1980 through the latest complete calendar year on a 1-km grid (Figures 3 and 4) that covers the contiguous U.S., Mexico, and Canada (south of 52°N), and are updated annually. One also can obtain monthly and annual climatological summaries for selected Daymet variables.

PRISM

The Parameter-elevation Regression on Independent Slopes Model (PRISM) dataset is based on meteorological station data interpolated to a 4-km grid (Figures 3 and 4) across the contiguous U.S. using a human-expert and statistical knowledge-based system (Daly et al. 2002). PRISM data address the issues of complex terrain, particular climatic features like rain shadows, and station-sparse regions by accounting for physiographic features such as the elevation at and vertical layer in which a grid cell occurs, observations at several meteorological stations of varying proximity to a grid cell, and the topographic orientation of a grid cell. Station records used as input for daily PRISM data are from several observational networks, and the resulting grids are subject to comparison against long-term average patterns

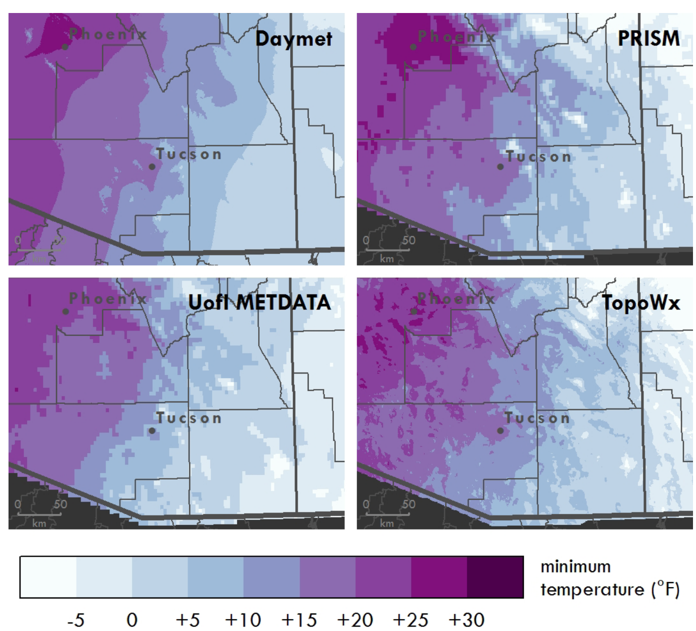

Figure 3. Minimum temperatures over southeastern Arizona on February 4, 2011, as modeled by Daymet (upper left), PRISM (upper right), UofI METDATA (lower left), and TopoWx (lower right). At that time, a cold, Arctic air mass had settled over the region, bringing with it multiple days of record and near-record low temperatures (http://www.wrh.noaa.gov/twc/climate/monthly/feb11.php).

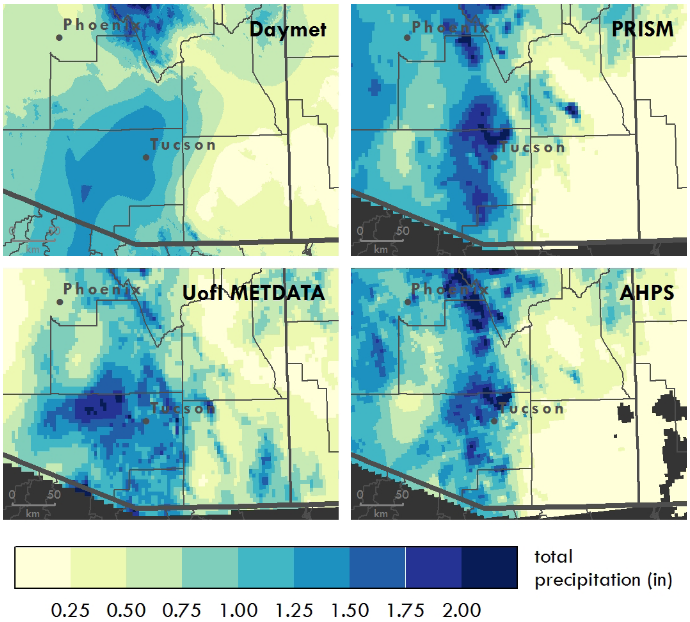

Figure 4. Total precipitation over southeastern Arizona on November 23, 2013, as modeled by Daymet (upper left), PRISM (upper right), UofI METDATA (lower left), and AHPS (lower right). During this time, a cut-off low pressure system – a storm system that is displaced from the jet stream – brought relatively high rainfall to the area over a multiple-day period (http://www.wrh.noaa.gov/twc/climate/monthly/nov13.php).

and advanced quality control measures (Daly et al. 2002; http://www.prism.oregonstate.edu/recent/). Daily PRISM data span the time period from 1981 to the present, and model minimum temperature, maximum temperature, and total precipitation (Table 1). Total precipitation represents amounts of rain and the water equivalent of snow. Since 2002, modeling of precipitation additionally includes radar estimates. Updates to the daily PRISM dataset are sub-weekly. Monthly climatological summaries of PRISM data from 1895 to the present also are available, as are 30-year (1981-2010) averages.

UofI METDATA

Methods to generate the University of Idaho Gridded Surface Meteorological Data dataset (UofI METDATA; Abatzoglou 2011) are a hybrid technique that combines the spatial resolution and detail of PRISM data (Daly et al. 2002) with the temporal resolution and expanded list of meteorological variables from Phase 2 of the North American Land Data Assimilation System (NLDAS-2; Mitchell et al. 2004). Meteorological variables from NLDAS-2 are based primarily on data from the North American Regional Reanalysis (Mesinger et al. 2006). Reanalysis is an approach to generate atmospheric data through models that assimilate a variety of observations such as those from meteorological stations, soundings, and satellites. Variables in the UofI METDATA dataset are minimum and maximum temperature, precipitation amount and duration, relative and specific humidity, surface downward shortwave radiation, and wind velocity (Table 1; http://metdata.northwestknowledge.net/). These gridded data are directly compared to station data from several observational networks, with validation primarily focused over the complex terrain of the western U.S. and split between the cool (October-April) and warm (May-September) seasons. Like PRISM data, the UofI METDATA is available on a 4-km grid (Figures 3 and 4) that covers the contiguous U.S. Daily UofI METDATA data are available from 1979 to the present, and are updated sub-weekly.

TopoWx

Based on meteorological station observations, as well as variables derived from digital elevation models and satellite measurements of land surface temperature, the Topography Weather (TopoWx) dataset provides minimum and maximum air temperature data (Table 1) on an approximately 800-m grid (Figure 3) for the contiguous U.S. from 1948 through 2012 (Oyler et al. 2014; http://www.ntsg.umt.edu/project/TopoWx). Prior to interpolation, temperature data from the Global Historical Climatology Network (GHCN; Menne et al. 2012), U.S. Forest Service and Bureau of Land Management Remote Automatic Weather Stations (RAWS), and Natural Resources Conservation Service Snowpack Telemetry (SNOTEL) networks are subject to quality assurance, homogenization, and missing value infilling procedures. This is to ensure that the influence of observational data inconsistencies such as changes in station location and instrumentation, bad observations, and record incompleteness on the TopoWx dataset is minimized. Interpolation of temperature data relies primarily on elevation data, and includes geostatistical kriging and geographically weighted regression. It also incorporates remotely sensed land surface temperature in order to model factors relevant to temperature like surface reflectivity and land cover. Validation of the TopoWx dataset is through comparison of gridded output with small spans of selected station data records that were intentionally omitted from the initial modeling process. Updates to the TopoWx dataset will be on an annual basis, with the first update to the dataset expected in 2015 (J. Oyler, personal communication). Monthly averages also are available, as are 30-year (1981-2010) monthly climatologies.

AHPS

The National Weather Service provides a gridded dataset of daily precipitation totals (Table 1) for the contiguous U.S. and Puerto Rico through its Advanced Hydrologic Prediction Service (AHPS; http://water.weather.gov/precip/). For areas east of the continental divide, this dataset is derived from radar and satellite estimates of precipitation that are compared to and corrected for differences against ground-based gauge measurements (Lawrence et al. 2003). West of the continental divide where radar coverage is inadequate, gauge measurements are integrated with spatial patterns found in long-term averages of PRISM data (Daly et al. 2002) in order to generate near-real-time precipitation grids that consider elevational changes and other important physiographic features relevant to rain and snow across mountainous terrain. AHPS considers input data from all sources – radar, satellite, and ground-based gauges – when performing quality control. Daily AHPS data are available from 2005 to the present on a 4-km grid (Figure 4), and are updated daily.

Where and How to Access These Datasets

As gridded data with relatively fine spatial resolution covering an area the size of at least the contiguous U.S., these daily topoclimatic datasets are large products that can make data procurement challenging. The use of file transfer protocol (FTP), a way to move data from a remote host to a local one, is common to all five of the gridded daily topoclimatic datasets reviewed here. In many cases, however, the entire daily dataset for a particular year and variable make up the file, which can range from approximately 250 MB to 1 GB in size. Furthermore, the downloaded file still may require additional steps in selecting data for a smaller region of interest or defined period of time.

Fortunately, different approaches exist to remotely subset such large, gridded datasets before data files are downloaded. These methods allow users to extract desired parts of the entire dataset by specifying details like the spatial domain and time span of interest, and can greatly reduce the size of downloaded files. The combined use of Open-source Project for a Network Data Access Protocol (OPeNDAP; http://www.opendap.org/) with Thematic Real-Time Environmental Distributed Data Services (THREDDS; http://www.unidata.ucar.edu/software/thredds/current/tds/) data servers is one such approach that is common to three of the five gridded daily topoclimatic datasets reviewed here. Other customized tools that enable users to remotely subset these large, gridded datasets through Web-based user interfaces also are available.

Listing of such tools for the individual gridded daily topoclimatic datasets, along with where to find access to these data, follows.

Daymet

Additional information for and access to daily Daymet data is at http://daymet.ornl.gov/. Data are accessible directly through FTP and OPeNDAP/THREDDS, as well as with tools that extract data for single pixels or selected individual 2° x 2° tiles. There are approximately 15 tiles that, when combined, cover Arizona. In addition, Daymet data are available from the U.S. Geological Survey (USGS) Center for Integrated Data Analytics (CIDA) Geo Data Portal (http://cida.usgs.gov/gdp/), which allows users to specify the region, meteorological variable, and time span of interest through a Web map application.

PRISM

Daily PRISM data and supporting information are found at http://www.prism.oregonstate.edu/recent/. Users can download daily data for specified days, months, and years through a Web interface. Users also can download data files in bulk through an anonymous FTP service, and via an open Web service.

UofI METDATA

Further description of and access to daily UofI METDATA data is at http://metdata.northwestknowledge.net/. Data can be downloaded directly through FTP as files containing daily data for individual years and variables. UofI METDATA data also can be subsetted through the USGS CIDA Geo Data Portal (http://cida.usgs.gov/gdp/) and THREDDS server (http://cida.usgs.gov/thredds/catalog.html).

TopoWx

Users can find more information about and download daily TopoWx data at http://www.ntsg.umt.edu/project/TopoWx. Data are directly available through FTP as files containing daily data for individual years and variables. As with the UofI METDATA dataset, data from the TopoWx dataset also can be subsetted through the USGS CIDA Geo Data Portal (http://cida.usgs.gov/gdp/) and THREDDS server (http://cida.usgs.gov/thredds/catalog.html).

AHPS

Access and additional information for AHPS daily precipitation data are available at http://water.weather.gov/precip/download.php. It is possible to download daily data for selected dates via FTP, as well as for daily, weekly, monthly, and annual periods through a Web interface.

General Suitability of Gridded Daily Topoclimatic Datasets

Despite the value, sophistication, and wide-spread use of gridded daily topoclimatic datasets that are currently available, some limitations with these data still exist. Shortcomings common to all of the datasets reviewed in this bulletin are primarily related to the observational data used as input for the interpolation process and the spatial scale of the gridded data.

For example, as all of the reviewed gridded datasets are based on weather observations from a variety of station networks, they are subject to both the limited spatial coverage of these input data as well as its quality, which may have issues related to instrumentation changes or record length and completeness. TopoWx, the most recently developed topoclimatic dataset, has advanced the state-of-the-art of ensuring overall quality of observational input data, which is important for detecting long-term trends in meteorological variables. However, further improvements to this process are still possible (Oyler et al. 2014).

Although these gridded daily topoclimatic datasets are suitable for use over spatial scales that range from the state to individual watersheds, they are limited in their ability to model the influence that fine-scale terrain and surface features have on temperature and precipitation. Variations in elevation and minimum temperature within a grid cell, for example, will not be represented in these datasets and as a result, local cold-air drainage or sheltering that occurs over relatively small areas is not discernible.

Both of these example limitations have implications when it comes to employing gridded daily topoclimatic datasets for weather and climate data applications in Arizona. In general, maximum temperature may be better modeled than minimum temperature, as issues like cold-air drainage pose additional challenges to interpolation algorithms. Also, representation in the gridded datasets of precipitation during the cool season, when storms are broader in size, may be more accurate than of precipitation during the warm season that often is delivered by localized storms and more difficult to measure due to sparse station networks.

Users should carefully consider such limitations before and during application of these datasets (Daly 2006).

Moving Forward

Differences between and limitations of the gridded daily topoclimatic datasets reviewed here should encourage users to analyze more than one dataset and not rely solely on gridded data whenever possible.

Dissimilarities in the development of the individual datasets highlight the need to use gridded data from as many sources as possible. Utilization of multiple gridded datasets will help address possible weaknesses that include interpolation method biases, biases in data observations from different station networks, and differences in horizontal resolution. Also, use of multiple datasets may allow users potentially to obtain a better understanding of past temperature and precipitation in Arizona.

Further understanding of not only historical weather and climate, but also the accuracy of gridded datasets, is possible by comparing data values of station-based observations not used in the development of the gridded dataset with those of the overlying grid cell (e.g., McEvoy et al. 2014; Table 2). One source of such station data is the Arizona Meteorological Network (AZMET; http://ag.arizona.edu/azmet/), which provides weather data and information from a group of automated stations in the central and southern parts of the state. Examining daily values of temperature and precipitation at a single grid cell from topoclimatic datasets provides a reasonable estimate of local weather and climate, but as previously mentioned, will not depict fine-scale variations of these variables that are sometimes of interest to agricultural producers and natural resource managers. So, although gridded daily topoclimatic datasets are helpful for tracking meteorological conditions over complex terrain and long time periods, they are not a replacement for fine-scale monitoring.

Gridded daily topoclimatic datasets that have relatively coarser horizontal resolution than the ones reviewed here also exist. One such dataset is a long-term collection of meteorological variables and land surface fluxes derived in part from the Variable Infiltration Capacity hydrological model (Livneh et al. 2013; ftp://ftp.hydro.washington.edu/pub/blivneh/CONUS/). In addition to temperature and precipitation, this dataset contains data for variables such as evaporation, sensible and latent heat fluxes, solar radiation, wind, and humidity. Horizontal resolution of this dataset is ~12 km, and data are available from 1915 through 2011.

Several software environments will enable users to work with files from gridded daily topoclimatic datasets. For instance, high-level programming languages for statistical computing and graphics such as MATLAB® (http://www.mathworks.com/products/matlab/) and R (https://www.r-project.org/) can utilize approaches such as the combination of OPeNDAP and THREDDS to remotely subset these large, gridded datasets, and directly read the various file types in which the data are made available. Opening these files in spreadsheets also is an option, particularly if time series of meteorological variables for a single pixel are of interest. However, download options for data in tabular form are limited and only available through Web-based user interfaces such as the Daymet Single Pixel Extraction Tool (http://daymet.ornl.gov/singlepixel.html) and PRISM Data Explorer (http://www.prism.oregonstate.edu/explorer/).

The increase in gridded daily topoclimatic datasets as a response to growing demand for spatially and temporally complete meteorological data helps lower some of the barriers for those in Arizona agriculture and natural resources who need historical daily surface weather data. Whether for ecological, crop, livestock, hydrological, forestry, or horticultural applications, understanding and thoughtful

Table 2. Comparison of gridded daily topoclimatic dataset values for temperature and precipitation with those from the Arizona Meteorological Network (AZMET) Tucson station on dates used in Figures 3 and 4. Values for gridded datasets are for the single pixel in which the AZMET Tucson station (32°16'49"N, 110°56'45"W; https://ag.arizona.edu/azmet/locate.html) is located.

	February 4, 2011 – minimum temperature (°F)	November 23, 2013 – total precipitation (in)
Station data		
AZMET Tucson	15.8	0.80
Gridded data		
Daymet	16.7	1.34
PRISM	15.9	1.79
UofI METDATA	9.8	1.45
TopoWx	15.7	n/a
AHPS	n/a	1.63

use of these datasets will allow users to extract additional information about Arizona's weather and climate.

Some example online applications of these datasets include:

- NOAA-NWS AHPS Precipitation Monitoring (AHPS): http://water.weather.gov/precip/
- WestMap (PRISM): http://www.cefa.dri.edu/Westmap/
- WestWide Drought Tracker (PRISM): http://www.wrcc.dri.edu/wwdt/

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College of Agriculture & Life Sciences
Cooperative Extension

The University of Arizona
College of Agriculture and Life Sciences
Tucson, Arizona 85721

Jeremy Weiss
Climate and Geospatial Extension Scientist
School of Natural Resources and the Environment
University of Arizona

Michael Crimmins
Climate Science Extension Specialist
Soil, Water and Environmental Science
University of Arizona

Contact :
Jeremy Weiss
jlweiss@email.arizona.edu

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