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Combined location online weather data: easy-to-use targeted weather analysis for agriculture

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Abstract
The continuing effects of climate change require farmers and growers to have greater understanding of how these changes affect crop production. However, while climatic data is generally available to help provide much of that understanding, it can often be in a form not easy to digest. The proposed Combined Location Online Weather Data (CLOWD) framework is an easy-to-use online platform for analysing recent and historical weather data of any location within Australia at the click of a map. CLOWD requires no programming skills and operates in any HTML5 web browser on PC and mobile devices. It enables comparison between current and previous growing seasons over a range of environmental parameters, and can create a plain-English PDF report for offline use, using natural language generation (NLG). This paper details the platform, the design decisions taken and outlines how farmers and growers can use CLOWD to better understand current growing conditions. Prototypes of CLOWD are now online for PCs and smartphones.

Keywords Weather data · Analysis · Climate change · Smartphone · Agriculture

1 Introduction

The collection and analysis of weather data has long been a fundamental part of the agriculture industry (Hubbard et al. 1983; Wilks and Wilby 1999). However, as the effects of climate change continue to play out across the globe, data analysis is playing an ever-increasing role in understanding those effects. In Australia, daily weather data is continuously recorded through a nation-wide series of weather stations under the guidance of the Australian Bureau of Meteorology. This data is collated each day by the SILO (Scientific Information for Land Owners) database project, hosted by the Queensland Government Department of Environment and Science[1] (Jeffrey et al. 2001). For a number of weather station locations, this SILO data is available dating back as far as 1899.

[1] SILO project - https://www.longpaddock.qld.gov.au/silo/

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The SILO project provides access to this raw data through its website. However, there is the opportunity to deliver more targeted data analysis, particularly for agricultural purposes and easier access on mobile devices. This paper introduces the proposed Combined Location Online Weather Data (CLOWD) framework that focuses on these goals. CLOWD enables users to choose the location and start date for data analysis, thereby enabling a focus on local growing seasons. It also locally-computes additional data, including growing-degrees days (GDD) (McMaster and Wilhelm 1997) and incorporates natural language generation (NLG) (Reiter and Dale 1997) technology to auto-generate plain-language PDF reports.

Moreover, CLOWD requires only a standard (HTML5) web browser and an internet connection, thus, no additional applications need to be downloaded and installed on the user's device. Prototypes of the CLOWD platform are now available for PCs/laptops[2] and smartphones/tablets[3].

1.1 Original contributions

As will be detailed here, the original contributions of this paper include:

- A framework that enables comparative agriculture-focused weather data analysis to be performed on historical and recent Australian data using a web browser on either a PC or smartphone.
- A framework that returns detailed weather analysis of any location in Australia with a single map-click.
- A framework that starts the growing season on any user-selected date in the year (day-zero) and initialises all data analysis to that date.
- A framework that incorporates NLG methods to help simplify understanding of chart trends.

While acronyms used frequently in this paper are listed in Table 1, this paper will now continue with a look at related research in Section 2. This will be followed by a summary of the study area and data sources in Section 3. Section 4 details the CLOWD framework and its impact on stakeholders. Additional locally-processed data analysis functions are covered in Section 5, with an example of discovered knowledge in rice production following in Section 6. Discussion of future research opportunities occurs in Section 7, while Section 8 concludes this paper.

2 Related work

Decision support tools (DSTs) are an increasingly important component in digital farming around the world (Rose et al. 2016; Hachimi et al. 2022) and those that incorporate smart systems, big data and artificial intelligence are considered part of 'Agriculture 4.0' (Zhai et al. 2020). However, research definitions of DSTs and the outcomes they provide are known to vary. A DST has been defined as 'a human-computer system which utilises data from various sources, aiming at providing farmers with a list of advice for supporting their decision-making under different circumstances', but one that does not go so far as to provide direct instructions

[2] CLOWD for PCs/laptops - https://clowd.csu.edu.au

[3] CLOWD for smartphones/tablets - https://clowds.csu.edu.au

Table 1 Table of definitions for additional acronyms used in this paper

API	Application Programming Interface	NLG	Natural Language Generation
CSS	Cascading Style Sheet	NSW	New South Wales
DST	Decision Support Tool	PDF	Portable Document Format
GDD	Growing Degree Days	UI	User Interface
HCI	Human-Computer Interaction	UX	User eXperience
HTML	HyperText Markup Language	VPD	Vapour-Pressure Deficit

(Zhai et al. 2020). However, other definitions are more broad, with agriculture-focused DSTs categorised alternatively as either 'generating a series of evidenced-based recommendations', or acting more as information systems, leaving the end user (in this case, a farmer) to come to their own conclusions (Rose et al. 2016).

Nevertheless, research suggests the use of DSTs over the last ten years has by no-means been universal. A research survey in 2016 revealed that the use of DSTs in both the U.K. and other regions was 'limited' (Rose et al. 2016). This result was further supported by research conducted in 2019 by Michels, Bonke and Musshoff (Michels et al. 2020). This research identified a very high level of technology adoption from a survey of 207 German farmers, with 95% of those surveyed using a smartphone, yet found that adoption of phone-based crop-protection DSTs was only 71% (Michels et al. 2020).

Moreover, the research by Michels et al attempted to identify the reasons why farmers in the survey chose or chose not to use the phone-based crop-protection DSTs and made some noteworthy findings. First, the analysis of farmer responses was applied to the Unified Theory of Acceptance and Use of Technology, which considers four key behavioural factors that include performance expectancy, effort expectancy, social norm and facilitating conditions (Venkatesh et al. 2003). In summary, performance expectancy is the level of improvement a user believes an app has made to their task performance, while effort expectancy is essentially the 'ease of use' a person feels using an app. Social norm is the level a user feels they should be expected to be using such a app, while facilitating conditions is the user's perception of how well existing technology supports the app's key functions (Michels et al. 2020; Venkatesh et al. 2003).

Given a survey asking which functions were considered the most useful in apps related to crop-protection, 77% of 198 respondents chose 'weather information' and 83% said they were already using it. The authors made the caveat that many smartphones already include weather information, but did not specify the type of weather information used by farmers and whether a built-in app featured such information. Nevertheless, weather information was perceived by respondents of the survey as the most useful of features (Michels et al. 2020). The second point was in considering facilitating conditions, the authors noted the importance of the smartphone being capable of installing the app (Michels et al. 2020). For example, an iOS (Apple) app will not install on Android devices and vice versa. Importantly, our proposed CLOWD framework bypasses this issue by being a web-based app that requires no additional software installation.

The third point from this research was the importance of a DST (in particular, the user interface) being easy to use (Michels et al. 2020). This point is supported also by Zhai et al. (2020) where one of the key challenges seen in developing of 'Agriculture 4.0' DSTs was simplifying the DST's graphical user interface. It is in light of these findings that our proposed CLOWD framework exists as two separate platforms - one for smartphones and one for PCs/laptops, each with a separate and targeted user interface.

3 Study area and data

The study area of the proposed framework is the continent of Australia, including the island of Tasmania. Located south of the equator between the Pacific and Indian oceans, the continent measures 7,688,287 square kilometres, with area calculations based on 1:100,000-scale coastline data captured from the GEODATA Coast 100K 2004 project (GeoscienceAustralia 2024).

Australia is a land of considerable climatic variability and highly dependent upon regional weather systems, including the El Niño-Southern Oscillation (Timmermann et al. 2018), that make the country susceptible to drought and bushfires (Abram et al. 2021). As a result, agricultural conditions can also vary greatly between seasons. A recent example involves the production of Australian rice, which is predominantly grown in the fertile Riverina district in southern New South Wales. The rice crop harvest of 2018 saw 623,000 tonnes of all varieties harvested. This fell to just 54,000 tonnes the following year due to significant drought conditions (SunRice 2019).

3.1 Source data

Data used by CLOWD is retrieved on-request from third-party sources via the CLOWD web server and the CLOWD user interface directly. These sources make their data available through a Creative Commons Attribution 4.0 (CC BY) licensing arrangement and appear in Table 2. The CLOWD system then supplements the data with its own additional analysis processes as required.

Data from the Scientific Information for Land Owners (SILO) project forms the basis of location-specific weather data used by CLOWD for analysis[4]. This data is captured by the SILO project from the Australian Bureau of Meteorology[5] following each day, such that SILO weather data is available up to yesterday. However, SILO lacks some additional attributes used by agriculture, such as Growing Degree Days (Section 5.1). These additional attributes, including all cumulative measures, are calculated ‘on the fly’ by the CLOWD app based on the user-selected date-origin or ‘start’ date. Altogether, 18 weather attributes are generated from SILO data, details of which appear in Table 3.

EOX IT Services is a provider of satellite imagery, including 2016-era spatial imagery captured from the Sentinel-2 satellite[6]. Dubbed ‘Sentinel-2 cloudless’, this 2016 capture is made available through CC BY 4.0 licensing via a web map tile service (WMTS). Although this version is now a number of years old, it provides sufficient clarity for the task at hand.

Geoscience Australia provides geospatial map data of the entire country through a CC-BY 4.0-licensed WMTS data source. This data forms CLOWD’s default map view and the map data is available via API online[7].

CLOWD also presents fire-incident geospatial data covering the Australian state of New South Wales provided by the NSW Rural Fire Service to software developers via an API. The data is CC-BY 4.0 licensed and the API is openly available[8]. This data is overlaid in CLOWD onto the map made available by Geoscience Australia. This provides CLOWD users with

4 SILO API - https://www.longpaddock.qld.gov.au/silo/api-documentation/

5 http://www.bom.gov.au/

6 Sentinel-2 imagery API - https://s2maps.eu/

7 Australia map API - https://services.ga.gov.au/gis/rest/services/NationalBaseMap/MapServer

8 NSW RFS API - https://www.rfs.nsw.gov.au/news-and-media/stay-up-to-date/feeds

Table 2 Online data sources featured in CLOWD

Data source	Application
Scientific Information for Land Owners	Recent & historical Australian weather data
Geoscience Australia	Geospatial mapping of Australia
EOX IT Services	2016/17 Sentinel-2 satellite imagery of Australia
New South Wales Rural Fire Service	Fire-incident geospatial data for New South Wales
NSW Dept. of Planning and Environment	SEED Initiative Soil type/fertility mapping

additional information, covering wildfires (known as 'bushfires' in Australia), as well as local incidents, such as hay bale/stack fires, useful for farmers and growers. The RFS updates its data every 30 minutes. At this time, CLOWD only presents fire-incident data for NSW.

The New South Wales Government Department of Planning and Environment developed the SEED Initiative as a central resource for Sharing and Enabling Environmental Data. CLOWD utilises the Soil Type and Soil Fertility maps[9] and are selectable within the CLOWD user interface.

4 CLOWD development framework

The proposed CLOWD framework, shown in Fig. 1, is divided into two sections. First, the user interface or 'front end' controls delivery of information to the user via their web browser through the React open-source user interface platform. It also directly accesses location and soil map data from sources discussed in Section 3.1. Second, the web server-side or 'back end' section interacts with, as well as collects the required data from the SILO server. This section is built on the Node.js open-source JavaScript run-time platform. In all cases, data is accessed through CC BY 4.0-licensed APIs. These two sections required key decisions be taken for various design elements, with consideration for their inter-disciplinary impacts.

4.1 The user interface design

The user interface design centres on the user selecting a location anywhere within Australia on a zoom-able/clickable map and viewing the analysis of weather data as near to that location as data is available through a series of charts, each chart featuring one weather attribute. Thus, the goal is to keep the user interface as simple as possible to facilitate ease and speed of use.

Moreover, to better facilitate its use on different screen sizes, two versions of the user interface have been developed - a six-charted version for large/high-resolution PC and laptop screens as shown in Fig. 2, along with a second single-chart screen version for smartphones, shown in Fig. 3. Thus, following research in Section 2, the purpose of designing separate user interfaces was to make use of the inherent advantages of each platform. For example, larger-dimensioned PC/laptop screens enable the use of six side-by-side charts to more quickly determine trends between weather attributes. The single-charted phone version incorporates left/right-swipe control for fast access between charts on smaller screens, whilst maintaining

[9] Soil API - https://www.seed.nsw.gov.au/need-help/using-data-on-dataset-catalogue/using-seed-api-application-programming-interface

Table 3 Descriptions of the 18 weather attributes provided within CLOWD

Attribute	Description
Maximum Temperature	Maximum temperature recorded per 24 hours (°C)
Minimum Temperature	Minimum temperature recorded per 24 hours (°C)
Growing Degree Days (cumulative)	Accumulation of daily growing degree day (GDD) units since the user-selected Year Start date
Growing Degree Days (daily)	Daily measure of GDD calculated (see Section 5.1)
Rainfall (cumulative)	Accumulation of daily rainfall since the user-selected Year Start date (millimetres, mm)
Rainfall (daily)	Daily rainfall interpolated to the nearest SILO-logged weather station (mm)
Evaporation	Class-A pan observations of evaporation over the preceding 24 hours (mm)
Reference Evapotranspiration (Penman-Monteith FAO)	An estimate of reference evapotranspiration derived from the Penman-Monteith equation (FAO56) (mm)
Solar Radiation	Total incoming downward shortwave radiation, derived from cloud and sunshine duration estimates (MJ/m^2), Jeffrey et al. (2001)
Vapour Pressure	Current level of atmospheric moisture, measured in hectopascals (hPa)
Vapour Pressure Deficit	Difference between maximum moisture atmosphere can hold at saturation and current atmospheric moisture levels (hPa) (see Section 5.2)
Relative Humidity @ Max. Temp	Relative humidity (%) calculated at the time of maximum temperature
Relative Humidity @ Min. Temp	Relative humidity (%) calculated at the time of minimum temperature
Morton evaporation	Morton's shallow lake evaporation (mm) (Morton 1983)
Morton potential evapotranspiration	A crop non-specific representation of evapotranspiration rate of a short green crop fully shading the ground with an adequate-water soil profile if water was unlimited (mm)
Morton wet environment evapotranspiration	Potential (derived) evapotranspiration over a large area, assuming unlimited water (mm).
Class-A evaporation (calibrated estimate)	Synthesised estimate of Class-A pan evaporation using a regression model (mm) (Rayner et al. 2004)
Mean-sea-level pressure	A derived average of barometric pressure taken at sea-level (hPa)

readability. Users can choose between weather attributes using the Settings page, with the phone example shown in Fig. 6.

These design choices were also made on the basis of previous research in human-computer interaction (HCI) that identified the relationship between functional complexity and interaction simplicity required in modern UI design (Miraz et al. 2021; Satzinger and Olfman 1998). The methodology used in designing both interfaces is to maintain what is considered as 'internal consistency', which is the consistency of the interface across the application components. This can include consistency in placement and design, ensuring the user has a simple user-experience (UX). Research by Miniukovich et al. (2019) has more recently shown that usability (how easy a website is to use) is affected by readability (how easy it is

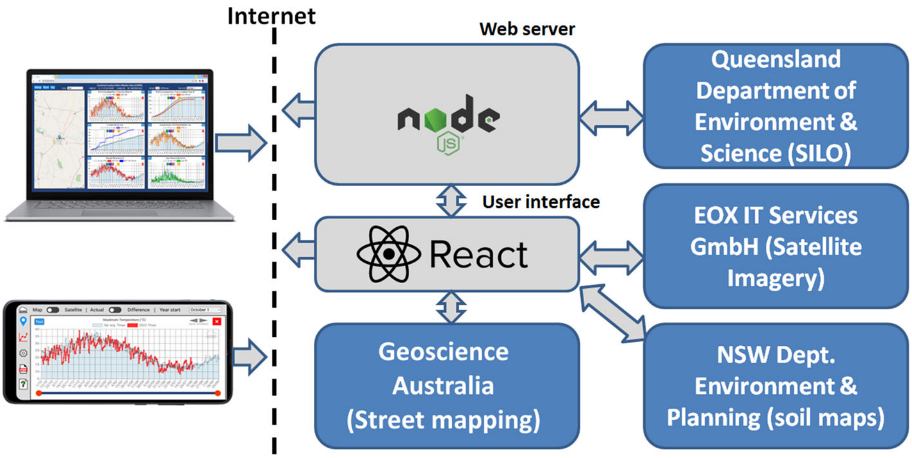

Fig. 1 The CLOWD framework features the Node.js run-time environment and React user interface development system to deliver the app to the user's device and access requested data from weather and geospatial data sources

to read). They identified a number of useful guidelines for improving the overall experience, including left-justified text, using font sizes greater than 12-point and the use of sans-serif style fonts. Where possible, these design guidelines have been implemented in the CLOWD user interface to further reduce any barriers for users to benefit from these web applications.

In both versions, the charts are customisable, in terms of the data and weather attributes they show. Moreover, the map allows a choice of a street view, satellite image, fire incidents (NSW only), soil type (NSW only) or estimated soil fertility (NSW only) of the area selected. All map options are coordinated such that they remain in lock-step as the map is moved and scaled.

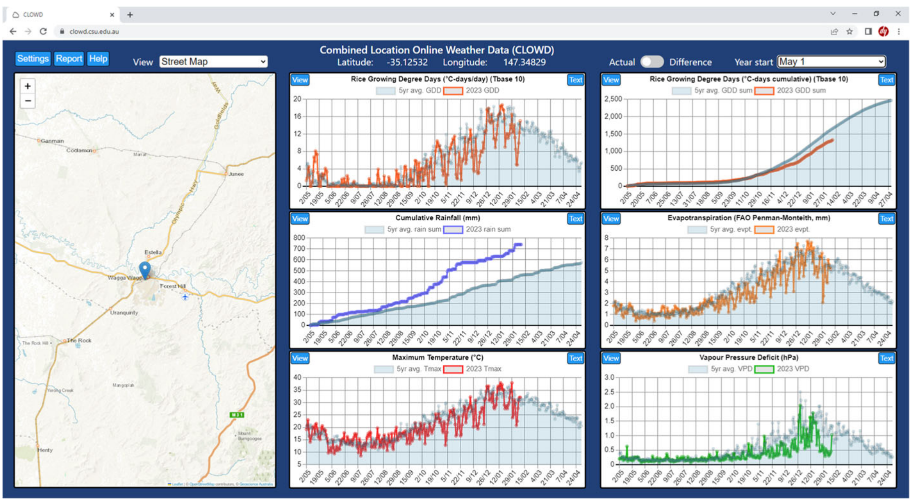

Fig. 2 The desktop computer version of CLOWD gives the user the ability to analyse multiple weather data for any location in Australia at the click of a map

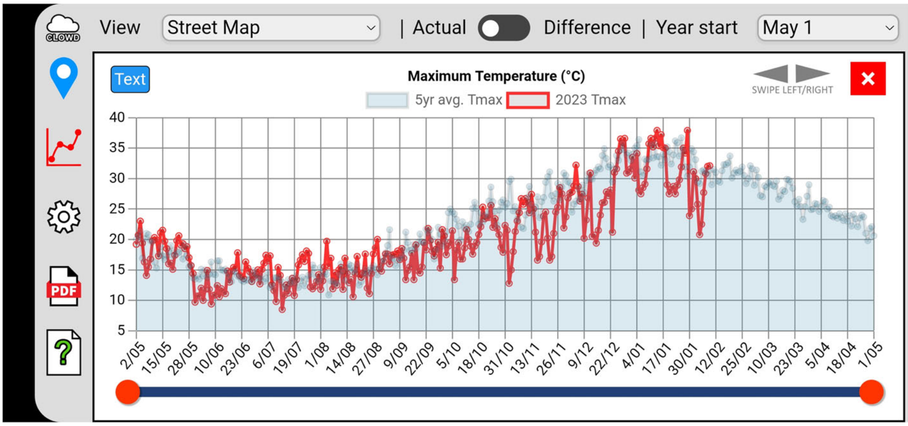

Fig. 3 The data charts available in the mobile version of CLOWD are selected by swiping either left or right on the chart screen and chart data can be magnified using the slide-magnifier control

The desire for a smooth and easy UX also led to the inclusion of a PDF (Portable Document File format) help/instruction manual to detail the CLOWD functionality. This appears inside a local PDF viewer on both versions. The importance of this delivery method is that it ensures the user always has the latest reference help document available as it is automatically downloaded and displayed upon pressing the 'Help' button.

4.1.1 Natural Language Generation (NLG) text

Research has long shown that understanding graphs and charts has been an important part of basic mathematical learning (Leinhardt et al. 1990), but also an area where users may struggle with understanding (Ojose 2011). To help mitigate this problem, each CLOWD chart incorporates a 'text' version automatically created through a programming technique called 'natural language generation' (NLG) (Reiter and Dale 1997). In its simplest form, NLG contains a series of pre-coded natural-language sentences that are then populated with the appropriate data and delivered to the user's screen. More complex forms automatically alter the sentence structures based on the data values. The purpose of NLG in CLOWD is to provide an overview of the chart's key points in a text form that can be read easily by those who may struggle in understanding charts. This feature can be seen in Fig. 4.

4.1.2 NLG algorithm

CLOWD implements its own custom NLG framework that endeavours to combine natural randomness with sentence structure. Each NLG textbox shown in Fig. 4 delivers three key summaries for the selected weather attribute - a) the value for yesterday and its comparison to the same day over the last five years, b) the average value over the previous week and its comparison for the same week over the last five years, and c) the previous peak over the last 30 days. As this data structure is fixed (only the values change), it could result in a monotonous appearance should every textbox feature the same sentences.

Instead, CLOWD incorporates a series of small sentence databases. One sentence is selected from each database to form the basis for presenting one of the key summaries. The sentences have been specifically crafted to deliver the exact same information, but their

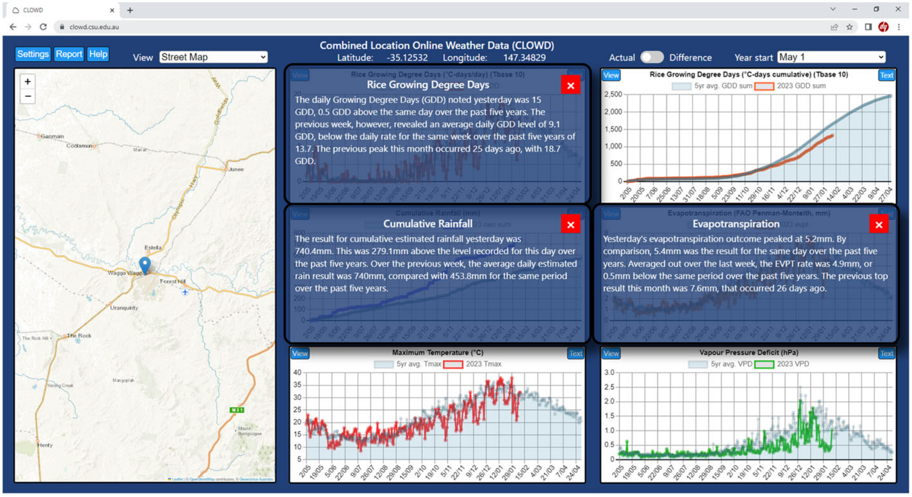

Fig. 4 Text used in the PDF report can be seen on individual data charts through each chart's Text button and is created automatically via Natural Language Generation (NLG)

varying structure and random selection delivers a more natural reading experience. This can be seen in the auto-generated PDF report (next section), where this natural variation is on display.

4.1.3 Auto-generated PDF report

The same NLG techniques are also combined to enable the creation of a location-specific weather analysis report. This PDF creation again takes place on the client device. On the PC/laptop version of CLOWD, the single-page PDF features all six visible selected charts in addition to their NLG text, as can be seen in Fig. 5, and can be viewed within the CLOWD application user interface. However, the PDF report can also be saved to the client device's local storage for further use or dissemination.

The smartphone version of the PDF report is similarly generated. However, the choice of charts and accompanying NLG text is determined by the chart rotation list created by the user within the CLOWD settings page. All 18 possible charts can be included in the smartphone PDF report, which is created with a similar '2x3'-layout (two columns of three charts per column) per page and automatically expands to include all selected charts (Fig. 6).

4.2 User interface technology framework

The user interface is developed using the React framework, originally developed by Facebook (now Meta) and made open-source in 2016 (Staff 2016). React describes itself as a 'JavaScript library for building user interfaces'. It simplifies the task of interacting between data manipulation processes within the JavaScript programming language and linking the outcomes of those processes with on-screen controls and displays. As the user interface appears within a standard web browser, this is still coded in standard HTML (HyperText Markup Language) and CSS (Cascading Style Sheets) languages. However, the additional analysis applied to the

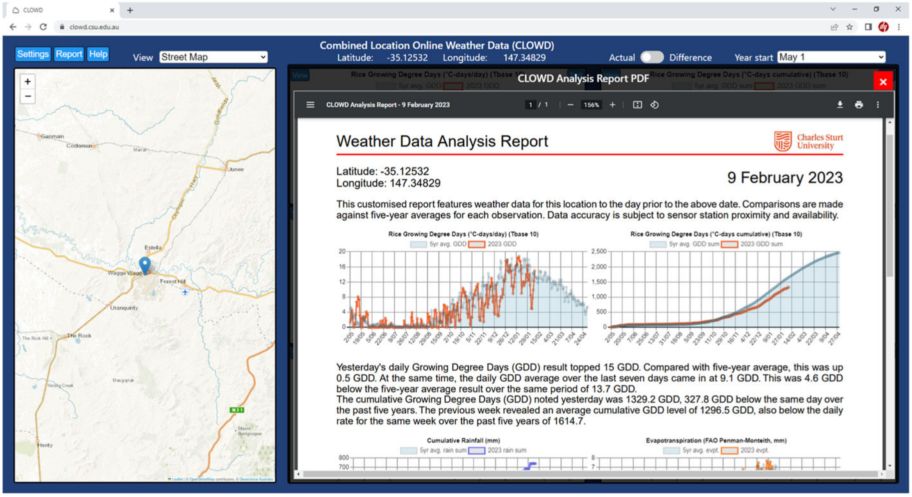

Fig. 5 CLOWD can auto-generate a single-page PDF report featuring the current-location data charts and text summary using NLG

retrieved weather data in CLOWD is a combination of Node.js (retrieval), React (processing) and custom JavaScript functions developed for CLOWD, a number of which will be detailed in Section 5.

Numerous additional libraries available via the Node.js Package Manager (NPM) are utilised within the React-powered user interface, including the Leaflet and React-leaflet map retrieval/display modules.

The on-device analysis does not appear to have a noticeably detrimental effect on client-device performance, including recent smartphones. Previous research has shown that smartphones are fast approaching - and even exceeding - the processing performance levels of current-generation laptops (Yates and Islam 2022).

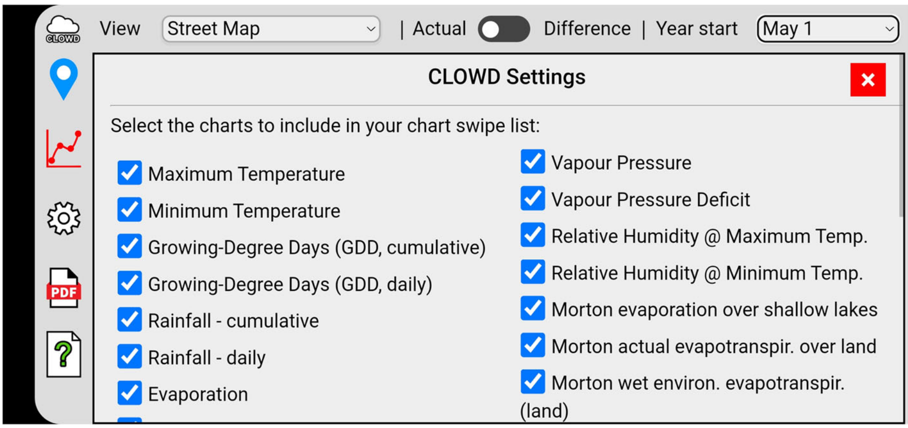

Fig. 6 In both the PC and smartphone versions of CLOWD, the user is able to select from 18 weather attributes for chart inclusion. These attributes are detailed in Table 3

4.3 The web server design

As is shown in Fig. 1, the web server provides a dual role in delivering the React user interface to the user's web browser, but also collecting the required data from third-party providers in response. This includes the selected-location weather attribute data.

The CLOWD web server is developed using the Node.js open-source run-time environment. Node.js is cross-platform, enabling it to run on Windows, Linux and macOS computing platforms. Thus, the CLOWD framework is also cross-platform, with the prototype tested on an Amazon Web Services Linux-based server. Node.js incorporates a library of third-party add-ons to provide additional functionality, such as the 'react-chartjs-2'[10] charting library, plus the Leaflet and React-leaflet[11] libraries mentioned earlier.

4.4 Impact for farmers and researchers

One of the key initial design decisions for CLOWD was to follow an 'agile' software development framework (Abrahamsson et al. 2017). In short, agile development is a broad set of principles that focuses on collaboration between stakeholders from different disciplines. It ensures stakeholders are able to make positive contributions, so that while the software functionality is built rapidly, regular communication and input from stakeholders ensures the design stays on-track to meet stakeholders' requirements.

For CLOWD, this involved fortnightly meetings (every two weeks) with agriculture and food science researchers from the Gulbali Institute at Charles Sturt University, as well as rice farmers and industry partners. The purpose of these meetings was to obtain feedback, first, with the initial 'rough-cut' software prototype and then, second, to illicit suggestions for additional features for the next two-week development period or 'sprint'.

An example of the impact this collaborative effort has had on CLOWD involved the implementation of an automatic Growing Degree Days (GDDs) calculation system. GDD is an important attribute for the agriculture industry and rice growers in particular, as it provides a quantitative measure to estimate the current phenology state of a growing crop. Growers can use this information to ensure farming processes are implemented accordingly. GDD is described in detail in Section 5.1.

Data analysis and knowledge discovery (the discovery of knowledge hidden within data using machine-learning and data mining techniques) invariably involve computer programming. The R programming language is an excellent tool for data analysis and a package called 'cropgrowdays' (Mortlock and Baker 2021) is available that enables R to retrieve data from the SILO source for further analysis. Both of these tools work extremely well, but they require programming knowledge, which inevitably limits the breadth of users able to use it.

However, by incorporating a graphical 'no-code' GDD implementation within CLOWD, research scientists and farmers can now generate specific GDD data for a specific period at a particular location without any programming knowledge. This has allowed rice farmers to gain greater understanding of the growing conditions. A similar use-case example involving vapour pressure deficit (VPD) is reported in Section 6.

Moreover, as will be discussed in the following section, CLOWD's GDD functionality has also been designed to support 22 different crop types, allowing growers of crops from barley and cotton to coffee and peanuts to easily generate custom GDD data for their specific needs.

[10] react-chartjs-2 - https://react-chartjs-2.js.org/

[11] React Leaflet - https://react-leaflet.js.org/

5 Data analysis

While the CLOWD framework utilises raw weather data from the SILO project, it also provides additional analysis of important agricultural parameters that are calculated locally on the client device. These include GDD and vapour-pressure deficit (VPD), along with analysis of recent temperatures (maximum and minimum) to provide targeted alerts.

5.1 Growing-degree days (GDD)

The biological processes of growing crops rely on heat and the mathematical measure of 'growing-degree days' (GDD) is commonly used to indicate the timing of these processes or phenology stages (McMaster and Wilhelm 1997). GDD is generally calculated daily and a crop accumulates GDD to provide an indication of the likely current phenology or growth stage. While the SILO project does not calculate GDD, it provides daily minimum and maximum temperatures and can be calculated on the client device. The daily equation takes the form:

$$GDD = [(T_{\max} + T_{\min})/2] - T_{base} \tag{1}$$

where $T_{\max}$ is the maximum temperature over the 24 hour period, $T_{\min}$ the minimum temperature and T_{base} the crop-specific threshold temperature (McMaster and Wilhelm 1997). However, as the work by McMaster and Wilhelm (1997) examines, there are two interpretations for how GDD is calculated, with regards to when the daily average temperature is below the base temperature, T_{base}. The first is that if the result of the GDD calculation is less than zero, it is converted to zero (that is, it can never be negative). The second is if either $T_{\max}$ or $T_{\min}$ are less than T_{base}, these individual components are set to T_{base}. At present, the CLOWD framework implements the first interpretation. Moreover, CLOWD allows the user to set T_{base} through the Settings option by selecting their particular crop, with 22 crop types to choose from.

While daily-GDD data is useful, it is commonly considered a cumulative measure, thus it is calculated as:

$$GDD_{sum} = \sum_{n=1}^{k} GDD_{(n)} \tag{2}$$

where $GDD_{(n)}$ is the GDD measure for the n^{th} day in the growing season of k days, such that $n = [1..k]$. Phenology stages can be tracked based on the crop achieving a particular level of cumulative GDD, with the count beginning on the sowing date (the date CLOWD users would set as start or zero-day).

5.2 Vapour-Pressure Deficit (VPD)

The amount of water needed on a daily basis by a growing crop is dependent on the environmental vapour-pressure deficit (VPD) (Wang et al. 2004). Similarly to GDD, CLOWD calculates VPD using a series of equations (Zotarelli et al. 2010), based on raw data provided by the SILO project.

The first step is to calculate the average saturation vapour pressure, $e_{s(avg)}$. This is done by calculating the saturation vapour pressure at both $T_{\min}$ and $T_{\max}$ via the equations:

$$e_{s(T_{\min})} = 0.6108exp(\frac{17.27T_{\min}}{T_{\min} + 237.3}) \tag{3}$$

$$e_{s(T_{\max})} = 0.6108exp(\frac{17.27T_{\max}}{T_{\max} + 237.3}) \tag{4}$$

The two values are then averaged:

$$e_{s(avg)} = \frac{e_{s(T_{\max})} + e_{s(T_{\min})}}{2} \tag{5}$$

At this point, the actual vapour pressure (avp) is derived as a function of relative humidity:

$$avp = \frac{[e_{s(T_{\min})} \times (RH_{\max}/100)] + [e_{s(T_{\max})} \times (RH_{\min}/100)]}{2} \tag{6}$$

where $RH_{\max}$ is the maximum relative humidity and $RH_{\min}$, the minimum relative humidity, from SILO data. The assumption is also made here that the point of maximum vapour pressure occurs at the time of minimum relative humidity and vice versa (Sadler and Evans 1989) (SILO records relative humidity as percentage values, hence these values are divided by 100 to obtain a proportional factor).

Finally, the VPD is the difference between the average saturated vapour pressure and the actual vapour pressure:

$$VPD = e_{s(avg)} - avp \tag{7}$$

The CLOWD framework calculates VPD on-demand for each day on the client/user device before it is charted as required. A JavaScript function called ‘calculateVpd’ has been created and incorporates the above equations to calculate VPD as follows:

```
calculateVpd(tmax, tmin, rhmaxt, rhmint) {
   var svpMax = 0.6108 * Math.exp( (17.27 * tmax) / (tmax + 237.3) );
   var svpMin = 0.6108 * Math.exp( (17.27 * tmin) / (tmin + 237.3) );
   var avgSvp = (svpMax + svpMin)/2.0;
   var avp = ( (svpMin * (rhmaxt/100)) + (svpMax * (rhmint/100)) ) / 2.0;
   return avgSvp - avp;
}
```

This function takes in the parameters $T_{\max}$, $T_{\min}$, $RH_{\min T}$ and $RH_{\max T}$ retrieved from the SILO data for the user-selected location and returns the calculated VPD value.

5.3 Weather analysis alerts

Weather conditions can have a detrimental effect on crop quality and yield. In Australia, it is generally recognised that night-time temperatures below 15°C can cause spikelet sterility during the microspore phenology stage in varieties of rice (Farrell et al. 2006) and affect head rice yield. However, this night-time temperature threshold varies not just between rice varieties but crop varieties also (Farrell et al. 2006). Thus, a method that delivers an automated and customisable alert to crop growers could prove valuable.

The CLOWD framework provides this alert system and is selectable by the user within the CLOWD settings page. An example is shown in Fig. 7. As the user selects a new location and in addition to the weather data for that location being downloaded from the SILO server, the preceding nine days are analysed for maximum and minimum temperature. If these temperatures are outside the threshold selected by the user (also chosen in the settings page),

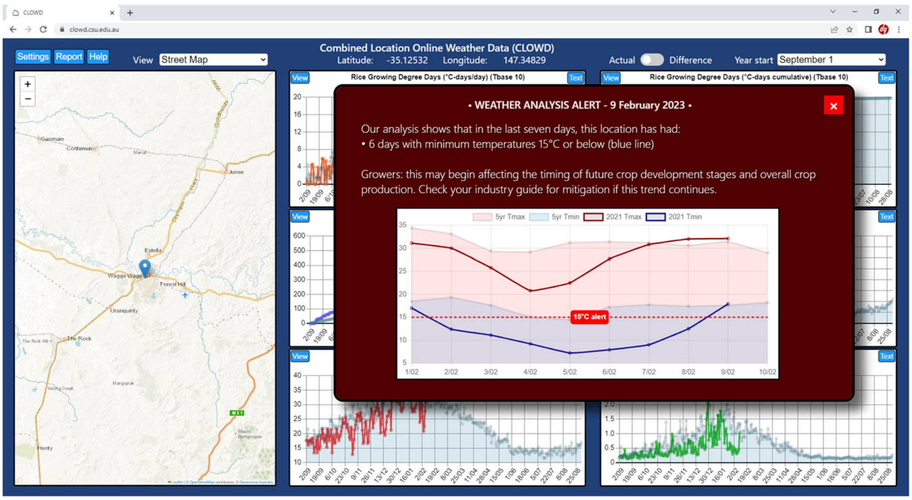

Fig. 7 Weather alerts are automatically generated when the maximum or minimum temperature exceeds the threshold set by the user in the CLOWD settings, which can also be deactivated by the user

an alert pop-up window appears to notify the user that recent temperatures are outside the threshold and that additional crop care may be required. The threshold temperature setting is stored locally within the client device's web browser and activated as chosen by the alert-settings option.

6 Knowledge discovery

The CLOWD framework does not provide the traditional DST response of telling a farmer or user when to perform a task or which task to perform. Rather, it is designed to enable the user to quickly identify weather patterns that may affect or explain certain crop outcomes.

During the 2021/22 rice growing season in southern New South Wales, it was noted that rice crops were maturing or reaching the 'harvest' stage later than expected. One of the key growth parameters that affects the timing of the various rice phenology stages is VPD. A high VPD is seen to accelerate plant development by pulling nutrient-containing water through the plant, aiding that development, whereas a low VPD slows down that development process (Noh and Lee 2022). Moreover, it has been reported that lower relative humidity and higher VPD can lead to higher head rice yield (Zhao and Fitzgerald 2013).

As noted in Section 5.2, CLOWD calculates its own VPD analysis, allowing comparison of the current growing season against any one of the previous five seasons or the five as an average. Using the smartphone version of CLOWD and the framework's 'difference' feature, it was seen that at the chosen southern New South Wales location, the VPD was below the five-year average for almost the entirety of a six-week period between panicle initiation and grain maturity. This can be seen in Fig. 8. While VPD may not have been the only cause for late maturation, the fact this below-average period occurred is noteworthy nonetheless.

The pictured view in Fig. 8 was achieved by selecting the map location, swiping to the VPD chart and switching on the 'difference' mode to show the chart data-value differences between the current season and the previous five-year average (the default comparison setting).

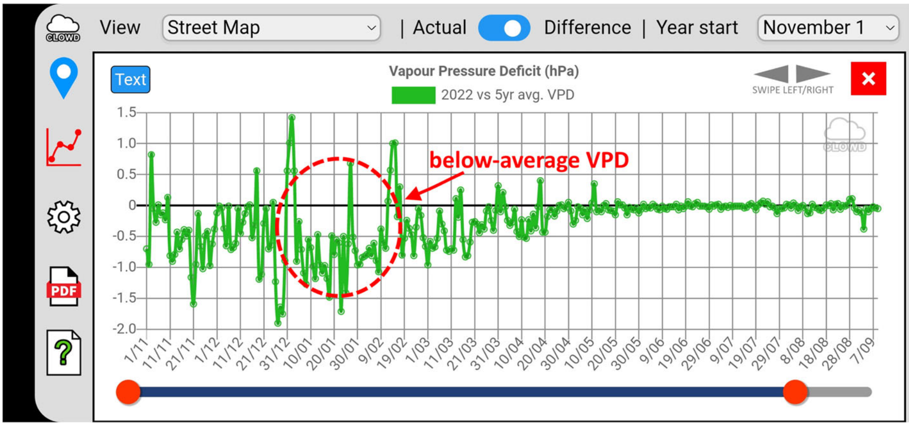

Fig. 8 Analysis using CLOWD's difference feature shows a period of below-average VPD during the key rice growth stage between panicle initiation and grain maturity at a selected rice-growing location

7 Discussion and research opportunities

While CLOWD has specific features aimed towards the agriculture industry (for example, the GDD charts), it is not limited to this industry. The new framework may have application in any field where fast analysis of recent or historical weather data is required, including bush/wildfires (Wilson et al. 2022) or flood mitigation (Chen et al. 2012). Further research is also being conducted to expand the CLOWD framework to include weather forecasting, allowing the addition of weather warnings, depending on the location and the warning-temperature settings selected. Moreover, the recent addition of the fire incident map data for New South Wales made available by the New South Wales Rural Fire Service is evidence of the possibilities available.

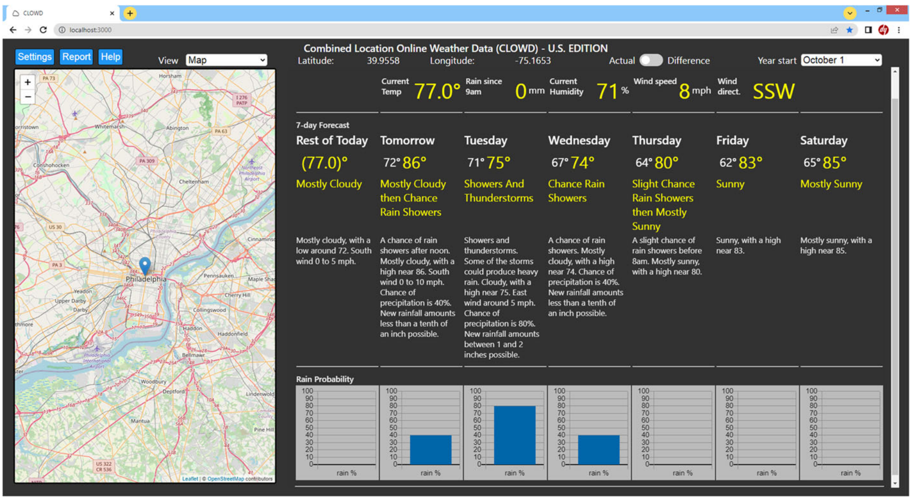

Fig. 9 An early prototype of a U.S. version of CLOWD showing location current and forecast weather using freely-available data from the U.S. National Oceanic and Atmosphere Administration (NOAA)

While the initial version of CLOWD is designed for Australia, the potential to transfer the framework to other geographic locations has been tested, with a working-prototype built around freely-accessible data made available by the U.S. National Oceanic and Atmospheric Administration (NOAA). This prototype, shown in Fig. 9, provides current weather conditions and a seven-day forecast (with percentage rain probability) for any location in the United States by clicking on the left-side map. Time permitting, our aim is to further complete this prototype and make it available for use.

Nevertheless, the surveys noted previously in Section 2 (Michels et al. 2020; Venkatesh et al. 2003) identified key areas for researchers and DST developers to consider in future research. First, the below-expected take-up of phone-based DSTs provides the opportunity for the software and agricultural industries to collaborate on improved phone solutions. Second, better understanding of farmer needs and expectations, particularly with regards to ease of application installation and ease of use will help improve uptake. This also includes easing the learning curve on graphical user interfaces.

8 Conclusion

Changing climate conditions are continuing to affect agricultural systems globally. This underlines the need for farmers and growers to have access to short- and long-term weather data to assist them in making the best decisions to achieve optimum outcomes. However, previous research has noted that despite the ubiquity of smartphone technology, the use of these ‘decision support tools’ (DST) has not been universal. Moreover, the importance of a good user interface design to ensure a positive user experience has also been noted as a key factor in DST design moving forward. With these findings in mind, the proposed Combined Location Online Weather Data or ‘CLOWD’ platform provides an easy-to-use method that is accessible from many computing devices and requires only a web browser. It features device-specific UIs and incorporates natural language generation (NLG) methods to simplify the understanding of the individual weather charts CLOWD provides. It is currently available as two separate prototypes - https://clowd.csu.edu.au for desktop/laptop computers, https://clowds.csu.edu.au for iOS and Android smartphones. While CLOWD was designed with Australian data in mind, a prototype implementation using U.S. weather data shows its potential for transfer to other locations, provided the required data is freely available.

Author Contributions Authors DY and AC contributed to initial concept. All authors contributed to user interface and feature design of the research software (CLOWD). First draft of manuscript was written by author DY and all authors reviewed and commented previous versions of the manuscript. All authors read and approved the final manuscript.

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Data Availability The data analysed during this current study is a location- and time-specific subset of weather data available from the SILO database created by the Queensland Government Department of Environment and Science. That is, the data varies depending on the map location selected by the user. This database can be accessed at https://www.longpaddock.qld.gov.au/silo/. This data is available under a Creative-Commons By-Attribution (CC-BY 4.0) license.

Declarations

Competing Interests Author RW is an employee of Ricegrowers Ltd. Other authors have no relevant interests to disclose.

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