IWAL—An Interactive Weather Analysis Laboratory

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PEDAGOGICAL BACKGROUND. Lecturers at ETH Zurich have a lot of pedagogical freedom for optimally designing their courses and choosing the most appropriate methodologies. Through the Innovedum Program, ETH Zurich supports and finances initiatives to explore new ways of sustainably improving teaching and learning. One of the core objectives of this program is to strengthen research-oriented learning. The interactive exploration of three-dimensional weather systems and their time-evolution with IWAL (Interactive Weather Analysis Laboratory) is such a research-oriented task, where students can individually investigate a particular aspect of a certain system with their own rationale. The active learning (Prince

2004) and curiosity-driven approaches are key characteristics of IWAL, which also distinguish it from very useful but more static approaches [e.g., the mathematical software tool for studying the structure of cyclones by Saraber and Heijboer (1994) and the extratropical cyclone atlas by Dacre et al. (2012)]. The pedagogical value of interactivity has also contributed to the development of an active learning approach for natural hazard management (Kos 2009) and an interactive engagement teaching approach in geosciences (Neves et al. 2013). An important pedagogical aspect of the setup of IWAL at ETH Zurich is that it offers access to analysis and forecast data from the European Centre for Medium-range Weather Forecasts (ECMWF),

FIG. 1. Screen shot of a typical IWAL session. The image shows the user interface and a Meteosat infrared image over Europe and northern Africa at 1200 UTC 6 Mar 2014. Note that the region is selected in the “viewport” on the left.

FIG. 2. Example visualization with several superimposed modules. The figure contains a Meteosat infrared image at 0600 UTC 5 Mar 2014 and contours for the zonal wind field at 350 hPa from operational ECMWF analyses. 48-h backward trajectories were calculated with pressure and PV values traced along their path, starting in a jet streak over North Africa. A skew T-logp diagram was additionally created at the starting point of the trajectories and is displayed at the lower left.

which allows the students to visually assess the quality of a model forecast over time and identify the structure and amplitude of forecast errors.

IWAL MODULES. The core feature of IWAL is the interactive visualization of atmospheric data in a web browser. A typical example of the look of an IWAL

session is shown in Fig. 1. IWAL offers different visualization types—for example, horizontal and vertical cross sections of 3D datasets, the visualization of 2D satellite images, and the interactive calculation and superimposition of trajectories. Each visualization type is accessible as an individual IWAL module, which provides several properties, such as the active time step, the visible data field, the vertical level, and the applied color mapping—all adjustable by the user. In addition, the two main visible display areas ("viewports") can be interactively translated and zoomed in and out.

A typical IWAL session starts by choosing the desired modules, adjusting the visualization properties, and invoking the creation of the actual plots based on the chosen settings. The plots are organized in the form of layers that are superimposed on top of each other. This allows the user to combine plots with a transparent background, such as contour plots or trajectories, with other plots (e.g., opaquely colored cross sections). An example for this is shown in Fig. 2.

The properties of each plot can be further adjusted and changed in order to interactively explore

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DOI:10.1175/BAMS-D-14-00020.1

A supplement to this article is available online (10.1175/BAMS-D-14-00020.2)

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FIG. 3. IWAL session with horizontal and vertical viewpoints. The horizontal viewport shows the zonal wind field at 300 hPa at 1200 UTC 6 Mar 2014; the vertical viewport shows zonal wind and potential temperature along a section across the North Atlantic jet stream.

the datasets. For example, the user can easily iterate over the available time steps, change the currently visualized data field (e.g., from “temperature” to “pressure”), or zoom in the view in order to observe small details of an interesting structure in the dataset. A special feature of all time-step properties is that their values are (optionally) synchronized between all visible plots.

In the case of horizontal cross sections of a 3D field, the user has the option to change the pressure level, which allows exploration of the vertical structures of the considered phenomenon. Further, IWAL provides an easy method for the creation of vertical cross sections. The user can select the start and end points directly by dragging markers in the horizontal viewport (Fig. 3). The vertical viewport can freely be translated and zoomed in and out in most interpolation modes, as is the case for the horizontal viewport. The current position of the vertical cross section, as well as the current mouse position, is shown and constantly updated in the horizontal viewport, allowing the user to get an impression of the spatial relation of the structures shown in the two main viewpoints. Note that a repositioning of the start and end points in the

horizontal viewport automatically redraws the vertical cross section accordingly, which greatly facilitates the interactive exploration of the data.

Figure 4 shows an example in the eastern South Pacific of an overlay of a water vapor satellite image and upper-level potential vorticity (PV) structures from two ECMWF forecasts with a lead time of 12 and 60 h, respectively. The short-term forecast reveals two prominent cutoffs (highlighted in colors) and one filament of stratospheric air (with $PV < -1$ pvu) in the same latitude band, which are associated with dark (dry) features in the satellite imagery (e.g., Appenzeller and Davies 1992). In contrast, the earlier forecast represents the two PV cutoffs with a clear spatial shift. Thanks to the straightforward superposition of observational and forecast data, such an analysis allows the students to visually assess the emergence of forecast errors.

A special visualization option is the plotting of skew T - $\log p$ thermodynamic diagrams at a selected location, as shown in the lower left corner of Fig. 2. The desired location can be selected directly in the horizontal viewport, using the same technique as for selecting the start and end positions of a vertical cross section.

FIG. 4. Superposition of PV at 300 hPa (in intervals of 1 PVU), calculated from ECMWF forecasts, and the water vapor satellite image in the eastern South Pacific, valid at 1200 UTC 6 Mar 2014. The right panel, for the 60-h forecast, shows a significant phase shift of the two cutoff features (highlighted in colors) between the forecast and satellite imagery; the left panel, for the 12-h forecast, shows a much better agreement.

Finally, the trajectory module provides a versatile method for computing and plotting trajectories together with data values traced along their way. The computation is initiated again by selecting the respective module and setting up the desired values of all plot options. These options include the start date and the time span of the trajectories and their total number, as well as the initial spatial distribution of all trajectories with respect to the selected starting point. The starting point itself is selected interactively in the same way as the position of the thermodynamic diagram. On the server side, the Lagrangian analysis tool (Wernli and Davies 1997) is used for creating the trajectory data. This module uses a separate viewport to display a table containing the position and values of additional fields traced along the trajectories (e.g., PV), as shown in Fig. 2.

VIEWPORTS AND DRAWING METHODS. The graphical user interface of IWAL is divided into three main parts: the central drawing area and two columns to its left and right. The left column primarily contains all controls for the selection and setup of the IWAL modules, as well as the properties of the active viewport and controls for global settings. The right column shows the list of all created plots, and the controls of the properties of the active plot.

The central area contains the two main horizontal and vertical viewports (see Fig. 3). IWAL can export the content of the two main viewports in the form of PNG image files.

The data visualizations offered by most IWAL modules are created directly on the IWAL server, based on the chosen values of the visualization parameters. The resulting plots are transferred to the client in the form of raster graphics images (PNG files). The module for the calculation and display of trajectory data, however, transfers the resulting datasets to the client using JSON (JavaScript Object Notation), a text-based open standard format for the exchange of simple data objects between a server and web application. The visualization on the client side is realized by canvas drawing functions rendering the trajectories as line strips. The usage of this alternative visualization technique is possible because the transferred datasets are relatively small compared to the meteorological fields visualized by other modules. It is also reasonable, since it decreases the required number of update requests sent to the server and thereby improves the overall performance of the application. More information about the software design of IWAL and the efficient caching and tiling scheme is available in the online supplement of this article.

FIG. 5. Analysis of a snowstorm in Finland at 1200 UTC 23 Nov 2008: (a) SLP (colors, intervals of 10 hPa, values in cyclone center are <950 hPa) and 300-hPa PV (black lines, labelled in PVU); (b) south-north oriented cross section with liquid water content (colors, peak values are about 0.4 g kg^{-1}) and PV (black lines, labelled in PVU) along the black line shown in (a); (c) backward trajectories calculated from the liquid water cloud in (b) superimposed on same fields as in (a); (d) the same trajectories as in (c) superimposed on 850-hPa liquid water content (colors, peak values are about 0.45 g kg^{-1}) and 850-hPa potential temperature (black lines, labeled in K). (Figure based on student presentation at ETH by Momme Hell and Remo Bebié.)

USER CASES, CASE STUDIES, AND SAVED PROGRAM STATES.

The IWAL implementation contains systems for the user authentication and for the management of different case studies. Each IWAL user either represents a single person or a whole group of persons (e.g., all students taking a certain course). A case study limits the range of accessible data and available plotting options provided by the IWAL server. For this, each case study is associated with data for a fixed time period, a limited set of data fields, and a set of available IWAL modules. Each user possesses a set of case studies from which he or she can choose. There are two main reasons for the implementation of these systems. First, they allow better control over the server load. The limiting of the accessible data and of the available plotting options for certain users can significantly reduce the number of different server requests. Second, these limitations can reduce the complexity confronting the user when working with IWAL, leading to a simpler and more convenient workflow for less experienced users.

All users working with a specific case study usually create their individual setup of data visualizations

and viewport settings. However, IWAL allows users of the same case study to save and share snapshots of their particular visualization setups, which are called “saved states.” In this way, for example, a teacher can prepare visualizations of important events to share with students later in class.

THE USE OF IWAL IN TEACHING.

During the last three years, IWAL has been used in two lecture courses at ETH Zurich. In the “Weather Systems” lecture course, students used IWAL to investigate the weather on the day of their birth as part of their homework, based upon ERA-Interim reanalysis data. In the “Weather Discussion” course, each year about 20 students were working at the same time in teams of two on different high-impact weather events. They used IWAL for interactively exploring the structure and evolution of their weather system, using satellite images, standard fields from ECMWF analyses, PV, and trajectories. At the end of the semester, they used IWAL visualizations to present their case study to the other students. Figure 5 shows, as an example for these case studies, IWAL visualizations of a

snowstorm in Helsinki. The sea level pressure (SLP) and the upper-level PV reveal a classical structure of a mature extratropical cyclone, with an upper-level trough overtaking the surface cyclone and a prominent ridge just downstream (Fig. 5a). The students then considered a south–north-oriented vertical section across the cyclone center and found a prominent region of supercooled cloud liquid water in the region of intense snowfall (Fig. 5b). They then started trajectories in the region of this low-level cloud and identified a transport of air and moisture from the eastern Mediterranean to Scandinavia as an essential element for this heavy snowfall event to occur (Figs. 5c,d). The students could produce these figures (and similar ones for earlier time instances) within a few hours. It is obvious that they very efficiently used the interactive features of IWAL to creatively investigate key aspects of the event by addressing, for example, the following questions: Was the snowfall related to an extratropical cyclone? Was there a strong upper-level forcing of the cyclone? Was large-scale moisture transport involved in the creation of this high-impact weather event?

Most students enjoyed working with IWAL. They quickly understood how to handle the tool and were motivated by the interactive possibilities. In an evaluation with an anonymous questionnaire in spring 2012, 19 out of 25 students rated the statement “I enjoyed working with IWAL” as “fully or rather true,” and 17 responded that “working with IWAL facilitated an in-depth meteorological analysis” was “fully or rather true.” These two questions correspond to the first two levels of the Kirkpatrick (2006) method of evaluating training programs, which are related to reaction and learning, respectively. Given these results from the student evaluation, we think that IWAL does well in terms of these criteria for evaluating pedagogical tools. The Kirkpatrick learning level has also been assessed by qualitatively comparing the progress in the students’ capability of independently exploring scientific questions with real data in classes where the students used IWAL and in earlier classes where IWAL was not yet available.

Also, compared to the approaches we used before (investigation of a static set of preproduced figures; teaching the students how to produce plots with standard graphics software), IWAL allows the user to rapidly focus on meteorology instead of technical challenges, and it offers, as expressed by a student in the end-of-term evaluation, “a wide range of

possibilities to explore different aspects of weather systems and to play around.” Another feedback stated “a hypothesis I managed to test was that two PV anomalies of the same sign circle around a common axis when they get close enough.” It is exactly for this curiosity-driven learning that IWAL has been developed.

PORTABILITY AND DEMO VERSION. Currently, IWAL is installed at ETH Zurich, and external users can access a demo version online at www.iwal.ethz.ch. Limbach (2013) provides background documentation on IWAL. Currently at ETH, the following ECMWF archives are accessible from IWAL: ERA-Interim reanalysis (1979–present), the last 7 days of the operational analysis, and the 7-day deterministic forecasts initialized at 0000 UTC for all days of the preceding week. Additionally, for several interesting case studies, operational analyses are permanently saved. Further archives can easily be integrated into IWAL with its administration tool. If IWAL is set up at another location, the main tasks are (i) to properly install the freely available third-party software, (ii) to set up a powerful web server, and (iii) to link the server to a (large) database (satellite images, reanalysis data, etc.), which can then be explored by IWAL.

ACKNOWLEDGMENTS. The development of IWAL has been supported by the ETH Innovedum Program. MeteoSwiss is acknowledged for providing access to the ECMWF data and the Meteosat images. We thank the three anonymous reviewers for their helpful comments and Urs Brändle for useful discussions.

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ISBN: 978-1-878220-98-1

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