Supporting Information

Figure S1. 500hPa specific humidity anomaly (10^{-3}kgkg^{-1}) in coloured contours and 700hPa vertical velocity anomaly (10^{-2}Pas^{-1}) in line contours for all phases of the Boreal Summer Intraseasonal Oscillation (BSISO) during June–September 1998–2018. The anomalies are computed against the summer mean climatology (June–September 1979–2018). The vertical velocity anomalies are smoothed using a 2-D Gaussian filter with a smoothing radius of ~200km. Solid (dashed) contour lines indicate anomalous decent (ascent). Coloured and line contours are not shown where the mean surface pressure is less than 500hPa and 700hPa respectively. Phase 0 represents BSISO events featuring an amplitude less than one.

Figure S2. 850hPa vector wind anomalies (ms^{-1}) for all phases of the Boreal Summer Intraseasonal Oscillation (BSISO) during June–September 1998–2018. The anomalies are computed against the summer mean climatology (June–September 1979–2018). Contours are greyed out where the mean surface pressure is less than 850hPa.

Figure S3. As in Figure S1, but for all phases of the Monsoon Intraseasonal Oscillation. Note the different contour interval for 500hPa specific humidity anomaly than shown in Figure S1.

Figure S4. As in Figure S2, but for all phases of the Monsoon Intraseasonal Oscillation.

Figure S5. As in Figure S1, but for all phases of the Madden-Julian Oscillation. Note the different contour interval for 500hPa specific humidity anomaly than shown in Figure S1.

Figure S6. As in Figure S2, but for all phases of the Madden-Julian Oscillation.

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First measurements of ocean and atmosphere in the Tropical North Atlantic using *Caravela*, a novel uncrewed surface vessel

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Introduction

In the tropics, air–sea interactions are an important driver of weather and climate variability and can seed extreme weather events. Robust, accurate and widespread observations at the air–sea interface can improve our understanding of air–sea interaction, help to validate coupled climate models and improve the initial conditions for weather forecasts. A crucial component of the air–sea interaction is the exchange of heat and moisture at the surface. When observing these fluxes, satellites and vessels can only take us so far. To make the next step in understanding air–sea interactions, a comprehensive network of flux measurement platforms, able to sample for extended periods of time, is needed (Cronin *et al.*, 2019).

Nowadays, there are a range of instruments spread across global oceans to capture in situ measurements as part of systems like the Global Ocean Observing System (GOOS) and the EUMETNET Surface Marine Programme. Some examples relevant to the collection of observations at the air–sea interface include the Argo network, moored and drifting buoys, and ships. However, these systems have their limitations: vessels are costly and thus only provide sparse coverage, while moorings rely on deployment and maintenance from a ship, another costly procedure. Argo floats have provided a step change in global coverage of ocean observations, but they typically only surface at 10-day intervals and so are unsuited to studying air–sea interactions on short time scales. Drifting buoys also require deployment by vessel and cannot be targeted to a region of interest, and most drifting platforms only measure near-surface ocean temperature and atmospheric pressure, in addition to recording their position. There are efforts to incorporate a range of meteorological and ocean sensors onto drifters (Centurioni *et al.*, 2019) but their Lagrangian nature still limits their use when a set location is to be studied.

The development of autonomous surface vessels allows targeted measurements of a wide suite of surface ocean and atmospheric data in particular regions of interest, over long time periods. These vessels will be a key component of future global in situ arrays of observation platforms for air–sea fluxes with high spatial resolution and minimal reliance on ship time. Ideally, these surface vessels would be non-polluting and powered by renewable resources, such as waves, wind and sun.

Autonomous vehicles

The use of autonomous vessels in air–sea interaction studies allows for measurements very close to the water surface, with minimal disturbance to the surrounding air and water parcels. Other advantages include: the ability to launch and recover the vessels from the shore, cutting down costs and reliance on ship time for study; the lack of emissions and low carbon footprint; and the ability to reach previously inaccessible areas. Examples of autonomous vessel deployments to date include Saildrones as part of the SPURS-2 campaign (Zhang *et al.*, 2019), to demonstrate their feasibility as air–sea interaction observational platforms, a wave glider studying air–sea interaction in Drake passage (Thomson and Girton, 2017) and the OCARINA platform developed by Bourras *et al.* (2014), deployed off the west coast of France as part of FROMVAR. It is apparent that the use of surface vehicles in flux deter-

RMetS Royal Meteorological Society

mination is still in its very early stages. The focus is currently on data acquisition, quality testing and determining the combinations of conditions under which autonomous surface vehicles struggle to operate.

AutoNaut

Following these studies, the University of East Anglia (UEA) worked with AutoNaut Ltd to develop an uncrewed surface vessel, named *Caravela*. Previous uses of AutoNaut vessels include scientific deployments (Johnston and Pierpoint, 2017), surveillance (Johnston and Poole, 2017) and environmental campaigns through AutoNaut's involvement in The Ocean Cleanup.[1]

The UEA's *Caravela* is a 5m-long surface vessel (shown during deployment in Figure 1 and described in Figure 2), with 0.8m draft and 1.5m high mast. AutoNaut's *Wave Foil Technology* generates the vessel's forward motion. This uses sprung foils at the front and aft of the vessel, which articulate to draw energy from the vessel's pitch and roll (Johnston and Pierpoint, 2017). The larger the waves, the more energy generated and the faster the forward motion of the vessel. An auxiliary thruster is also fitted on the aft foil to aid propulsion in difficult conditions. *Caravela* is a robust vessel, designed to withstand rough ocean conditions and in the event of capsize, self-right. *Caravela* can be operated in three different ways depending on proximity to the pilot. Up to 200m from the pilot, a joystick can be used to drive *Caravela* and engage the thruster, to allow for controlled movement at launch and retrieval sites. Up to around a kilometre from the pilot, *Caravela* can operate under 'local controls' in which the pilot sends commands from the piloting interface (called RCW) to *Caravela* over UHF radio. Finally, when beyond line of sight, the pilot can send commands from RCW over the Iridium satellite network. Within these piloting regimes, *Caravela* can operate under three modes: station mode, where *Caravela* circles a location at a specified radius, typically 25m; heading mode, in which a heading is set and kept regardless of course over ground; or track mode in which a series of waypoints are set and *Caravela* automatically adjusts heading to reach these points. This large range of operational modes opens many possibilities for meteorological and oceanographic measurement with an AutoNaut vessel.

Caravela has a modular monohull, allowing for integration of different sensor types and minimising risk of damage in case of water ingress. Four lithium-ion batteries recharged by three solar panels spanning *Caravela*'s surface are responsible for powering the onboard computer and sensors. The sensor package fitted on *Caravela* was selected to support the determination of air–sea fluxes and is described in Table 1, with locations on the platform shown in Figure 2.

Caravela's novel aspect is its ability to transport and release a profiling ocean glider, specifically a Seaglider. The Seaglider is a separate underwater autonomous vehicle piloted over Iridium, capable of profiling the ocean to 1000m through changes in its buoyancy. The Seaglider is visible inside *Caravela*'s release mechanism in Figure 2. The benefits of developing a Seaglider transport system are that the Seaglider can be deployed in a remote or challenging area, without the cost of sending a ship or endangering personnel. Additionally, the Seaglider can rest in *Caravela*'s glider release mechanism for a long period of time without significant battery wastage. This opens the opportunity to time the deployment of a Seaglider to study an event, like a monsoon or phytoplankton bloom, again without reliance on ship availability for deployment. The release mechanism does not allow for Seaglider recovery to *Caravela*, so it is still necessary to consider ship availability to collect the Seaglider. However, this provides many more opportunities for deployment than if a ship was needed for both deployment and recovery.

Deployment of an AutoNaut – data quality

The first full scientific deployment of *Caravela* took place from January to March 2020, as part of the Eurec4a campaign (Bony *et al*., 2017; Stevens *et al*., 2020). Eurec4a was developed to investigate the coupling

Figure 1. Photograph of Caravela *(an AutoNaut vessel) in front of the German* R/V Meteor *during the Eurec4a campaign. (Credit: Callum Rollo.)*

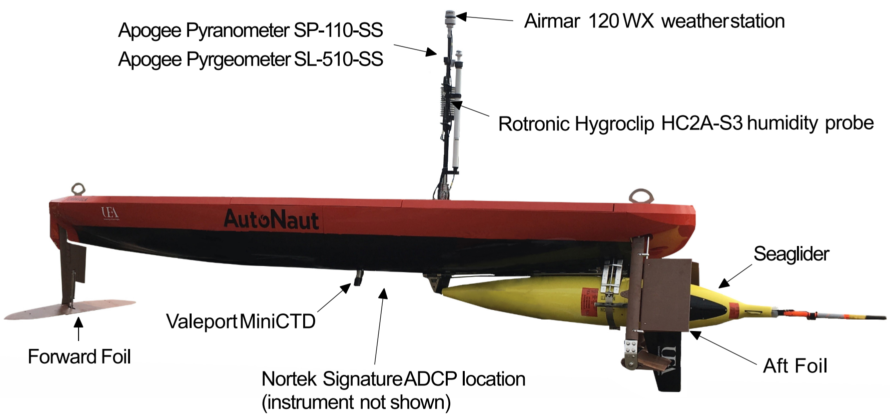

Figure 2. Labelled photograph of Caravela *and a Seaglider, describing the locations of meteorological and oceanographic sensors. The Nortek Signature1000 ADCP is not included in the figure but would be mounted below* Caravela*, level with the CTD.*

[1]https://theoceancleanup.com/

between clouds, circulation and climate but expanded to cover many themes within meteorology and oceanography that feed into climate research. UEA's contribution involved the preparation of *Caravela* in Barbados, where the vessel was deployed with the aid of the Barbados Coastguard on 22 January 2020.

Caravela travelled from Barbados to the study site and back over 33 days. This included 11 days occupying a 10km wide hourglass-shaped sampling pattern at the study site (upper right of Figure 3). On the outward journey, *Caravela* covered approximately 150km before the Seaglider was released to travel independently to the study site. Average speed over ground was approximately 0.34ms^{-1} whilst carrying the Seaglider, compared with 0.49ms^{-1} across the whole deployment. Unfortunately, we suspect entanglement of the Seaglider in Sargassum slowed *Caravela*, hence releasing the Seaglider earlier than planned on the outward journey. Fortuitously, *Caravela* and the Seaglider arrived separately at the study site within a day of one another, giving us an almost co-located dataset between the two platforms during outward transit.

The Airmar 120WX (Airmar) and Rotronic Hygroclip HC2A (Hygroclip) both measured air temperature on *Caravela*. When analysed, we discovered these instruments showed poor agreement. Both instruments were shaded and well ventilated. The Airmar is situated at the top of the mast (1.5m), approximately 0.5m above the Hygroclip. Comparisons with data from the *R/V Meteor* (Figure 4) shows consistency with the Hygroclip sensor. The Hygroclip time series stopped on 18 February due to sensor failure but we are satisfied with the quality of data obtained from the Hygroclip before failure. However, the Airmar does not provide the accuracy required to detect small temperature variations important in heat fluxes. It is often used as a sailing or fishing instrument and whilst useful for these applications, is not appropriate for our needs in terms of air temperature measurement. The Airmar instrument is also responsible for apparent wind data. This analysis is in progress so comprehensive assessment of the quality of Airmar wind data will be addressed in subsequent publications.

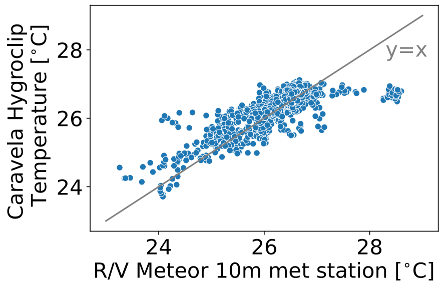

Figure 4. Comparison of air temperature measurement between a weather station on the R/V Meteor *and* Caravela*'s Hygroclip instrument, when the vessels are within 10km of one another. The median Hygroclip temperature value per minute was matched to the* R/V Meteor *data. From this we see that* Caravela*'s Hygroclip data agrees well the* R/V Meteor *and does not require correction.*

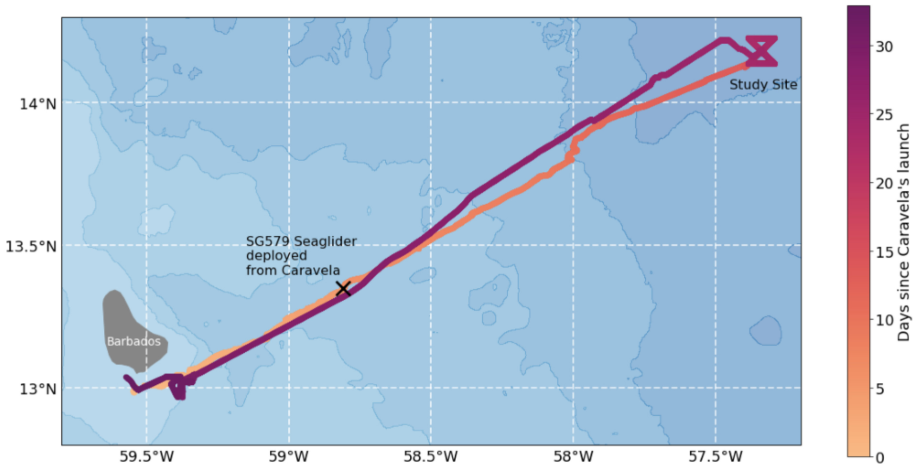

Figure 3. Track taken by Caravela *during the Eurec4a campaign, coloured by days since deployment from Barbados. The study site is labelled at the top right, where* Caravela *repeated the same bowtie pattern for 11 days. The release location of the Seaglider from the transport system below* Caravela *is marked in the figure. Bathymetry is shown in blue with contours at 1000m depth intervals.*

Table 1

Description of the parameters measured by Caravela during the Eurec4a deployment and the associated sensors.

Instrument	*Measurements*
Apogee Pyrgeometer SL-510-SS	Incoming longwave radiation (5–30μm)
Apogee Pyranometer SP-110-SS	Incoming shortwave radiation (360–1120nm)
Rotronic Hygroclip HC2A-S3 humidity probe	Air temperature, Humidity
Airmar 120 WX weather station	Wind velocity, Air temperature, Barometric pressure
Nortek Signature1000 ADCP	Near surface current velocity
Valeport MiniCTD	Sea surface temperature (SST), Conductivity, Water pressure

A time series of *Caravela*'s sea surface temperature (SST) data whilst at the study site was compared with Seaglider SST data (Figure 5). This uses three different Seagliders deployed in the study site throughout Eurec4a, the one released from below *Caravela* and two deployed from the *R/V Meteor*. We would expect to see a diurnal cycle in SST, which is clearly visible between 10–14 February. The measurements from the two platforms are consistent, albeit with substantial spatial and temporal variability evident.

Downwelling longwave (5–30μm) and shortwave (360–1120nm) radiation were measured by *Caravela* throughout the Eurec4a campaign because accurate measurements of these parameters are vital for heat flux estimation. The total air–sea heat flux is the sum of four fluxes: net longwave and shortwave radiative fluxes; surface latent heat flux; and sensible heat flux. Variability in incoming solar radiation throughout the day impacts surface heat flux and causes the diurnal cycle in SST (Figure 5). Figure 6 shows the diurnal cycle in shortwave (i.e. solar) radiation. We see significant variation of around 100Wm^{-2} in the longwave radiation (Figure 6).

Future work

Caravela offers continuous measurements of surface fluxes and surface conditions that are co-located with the HALO aircraft's flight circle during the Eurec4a campaign, as well as complements the measurements taken from the *R/V Meteor* on a meridional transect at 57°14.7′W. *Caravela*'s data will be valuable outside of our heat and momentum flux research, providing a stationary time series in Eurec4a where many other platforms had large spatial coverage. Having *Caravela* provide measurements in the marine boundary layer, co-located with flights by the HALO aircraft, will enhance atmospheric analysis within the wider scope

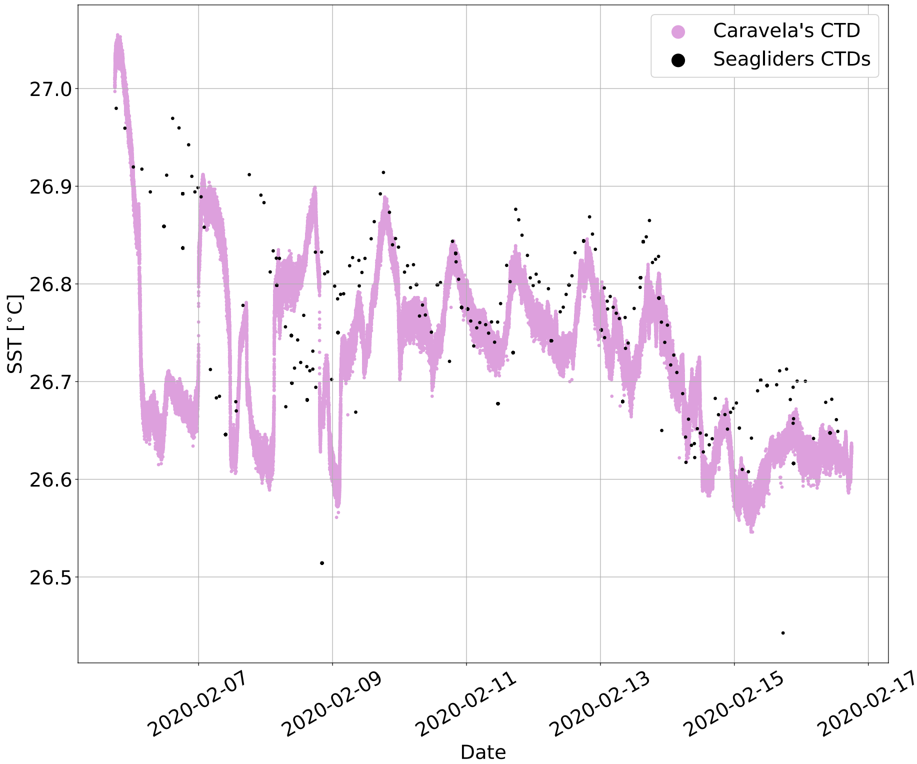

Figure 5. Time series of sea surface temperature (SST) data from Caravela*, measured 0.2m below the surface with data from three Seagliders at the same study site. The Seaglider data shows one measurement per dive, recorded nearest to the surface as the Seaglider ascended. Clear diurnal cycling in both Seaglider and* Caravela *data between 10 and 14 February can be seen, with spatial and temporal variability.*

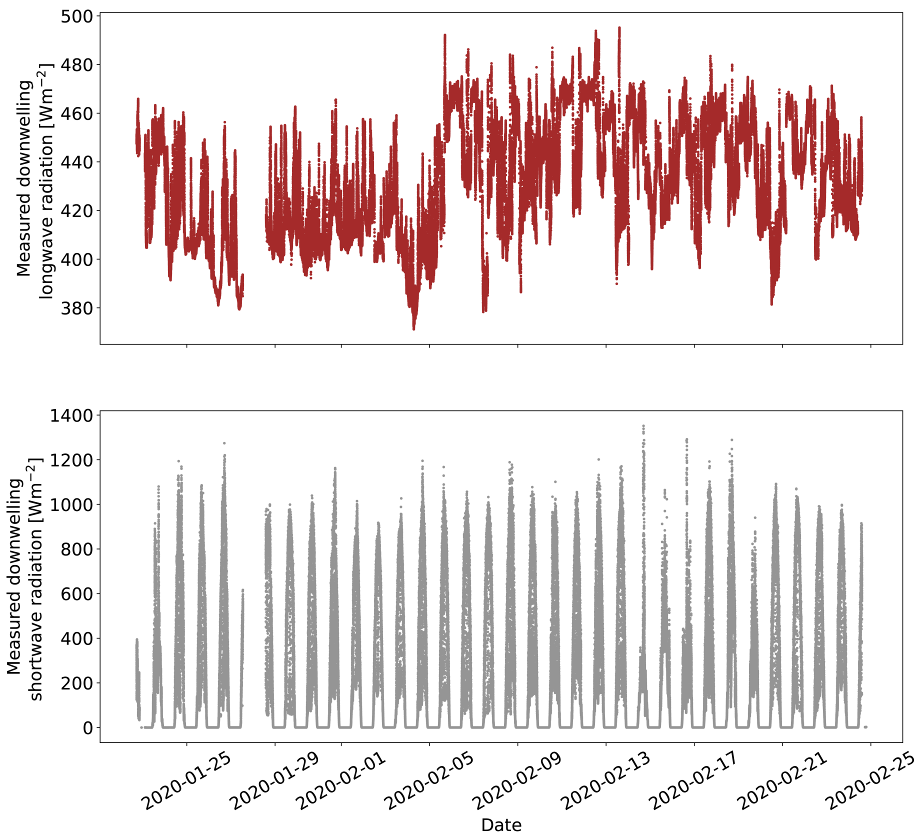

Figure 6. Time series of measured downwelling longwave (top) and shortwave (bottom) radiation on Caravela *during the Eurec4a deployment. These instruments performed well on* Caravela*; investigation into the impacts of vessel motion on these measurements is ongoing.*

of Eurec4a by providing true data at sea level. Without this, much coarser resolution satellite data or ship data further up from the sea surface would have been relied upon. This has scope to enhance the quality of boundary layer heat fluxes and understanding of the impacts on clouds at a local scale in the wider campaign.

UEA's future work with *Caravela* will first build on the observations from Eurec4a, calculating local heat and momentum fluxes between the ocean and atmosphere. Using time series of upper ocean heat content from the profiling gliders, we will estimate an upper ocean heat budget at the study site with the purpose of determining the dominant SST variability driver in the region. This would allow us to differentiate between SST variability based on surface heat fluxes and subsurface processes like mixing, entrainment or advection. We intend to do this work with observations alone, utilising data from *Caravela*, the Seaglider transported to the study site by *Caravela* and the two other Seagliders that were deployed from the *R/V Meteor*. Deriving the ocean mixed layer heat budget based solely on ocean and atmosphere observations is rare. If the analysis is successful, we intend to undertake a similar deployment in Antarctica, where in situ observations are even more scarce. We hope this work will provide a foundation for future air–sea interaction research based only on the use of autonomous observations.

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There are no conflicts of interest to declare.

Author Contributions

Elizabeth Siddle: Data curation; formal analysis; investigation; methodology; validation; visualization; writing-original draft; writing-review & editing. **Karen Heywood:** Conceptualization; investigation; project administration; resources; supervision; writing-review & editing. **Benjamin Webber:** Investigation; project administration; supervision; writing-review & editing. **Peter Bromley:** Supervision; writing-review & editing.

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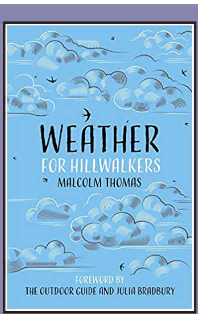
Book review



Weather for Hillwalkers – Second Edition

Malcolm Thomas

The History Press, 2019

Hardback £10.99

128 pp

ISBN 978-0-7509-9244-2

Mountain weather conditions can change dramatically from hour to hour, even minute to minute. Each year some walkers and climbers who venture into the hills underestimate the conditions they may have to face, and some pay with their lives as a consequence. What is weather like on the mountains? Why are mountains wetter? Why, in most cases, does it become colder higher up a mountain? These and many more questions are answered in this compact reference book.

A brief but poignant foreword is provided by walking enthusiast Julia Bradbury. In the Introduction which follows, Malcolm Thomas states: *'As we all know, professional forecasts are not always completely accurate and it is unlikely they ever will be. However, a knowledge of weather can help in the interpretation of weather forecasts.'* This book is particularly concerned with the mountains of the British Isles. It provides a clear insight as to why we have weather and provides a basic understanding of weather terminology such as highs and lows, warm and cold fronts, and air masses. The first five chapters – a large proportion of the book – deal with the weather in broad terms. The chapter concerning air masses is particularly useful. As well as information about the source of each air mass, the author also lists the most likely cloud base, visibility, wind direction, and weather that can be expected, and provides information for interpreting weather charts and making short-term forecasts from observations.

In subsequent chapters Thomas details how different weather elements can be affected by high ground, each topic accompanied by simply drawn, well-annotated diagrams. Clear and concise explanations are given to phenomena such as the temperature decrease with height as well as temperature inversions; exposure and wind chill; the funnelling of wind across a ridge or beneath an inversion, and where shelter might be found; katabatic and anabatic winds; enhancement of rainfall on windward slopes and mountain tops; the freezing level and the change of precipitation from rain to snow; and the correct procedures that should be adopted in a thunderstorm. The book ends with a useful glossary.

First published in softback format in 1995, Thomas's book became a classic while he was still a professional weather forecaster. The basic text and diagrams remain unchanged in this second edition, but I do feel an opportunity has been missed to enhance this excellent work with a few more colour images and diagrams throughout the book, besides those to be found in the chapter on cloud types. A section devoted to understanding avalanche risk and forecasting could have been added. Quite rightly, the final chapter regarding the types of weather forecast available and where to find them has been largely removed: many of the services listed in the original edition no longer exist and technology has significantly changed over the intervening 25 years or so. A new chapter covering current technology and a brief introduction to the multitude of forecasts and data now available on computers and mobile phones would have been useful additions, especially for the novice.

This book provides a valuable insight into mountain weather to both the beginner and experienced hillwalker and climber. It could be deemed an essential reference for anyone with a walking leader qualification or looking to gain one. I have used it as a source of reference for giving talks about mountain weather to my local hillwalking club.

Graham Denyer

doi: 10.1002/wea.3975

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