Spatial and temporal variations in near-surface energy fluxes in an Alpine valley under synoptically undisturbed and clear-sky conditions

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Abstract
Diurnal cycles of turbulent sensible and latent heat fluxes are typically closely related to the diurnal cycles of solar irradiation under synoptically undisturbed and clear-sky conditions. In mountainous terrain, large variations can occur in the topographic and surface properties, which modify the local radiation budget and thus turbulent energy fluxes and the surface energy balance. Another characteristic of mountainous terrain is local, thermally driven circulation systems, such as the slope- and valley-wind system, which can equally affect turbulent exchange. Observations of near-surface radiative and turbulent fluxes are presented from six eddy-covariance stations in an approximately east–west-oriented major Alpine valley for undisturbed and clear-sky conditions. Median diurnal cycles over the whole year are compared at the six sites and related to local terrain characteristics and the thermally driven wind systems. At a scale that is smaller than grid cells in current operational global forecast models, heat, moisture, and momentum fluxes show a large spatial variability in the magnitudes and their diurnal cycles. Lowest heat fluxes are observed on the north-facing sidewall, where solar irradiation and thus available energy are reduced compared with the valley floor and south-facing sidewall. Differences in the land surface characteristics further affect the partitioning of the available energy into sensible and latent heat fluxes. The median sensible heat flux reaches its daily peak already before solar noon at several sites, which appears to be related to the transition from down-valley to up-valley winds. In contrast to flat and homogeneous terrain, horizontal heat fluxes and lateral momentum fluxes can reach magnitudes that are similar to the magnitudes of vertical heat fluxes and longitudinal momentum fluxes, respectively.

KEYWORDS
complex terrain, diurnal cycles, surface energy balance, turbulent fluxes, valley boundary layer, valley wind circulation

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1 | INTRODUCTION

Solar radiation is the main driving mechanism for the Earth’s surface energy balance. In complex, mountainous topography, it can vary considerably from site to site, depending on the orientation and slope angle of the underlying surface, as well as on shadows cast by the surrounding mountains (Whiteman et al., 1989a; Whiteman, 2000; Matzinger et al., 2003; Hoch and Whiteman, 2010). The effect of slope exposure (i.e., slope angle and orientation) on the diurnal cycles of solar irradiation has been shown for slopes with varying slope angles and orientations and for different times of the year on the basis of idealized calculations and measurements, highlighting the large impact on the timing and magnitude of solar irradiation and on sunrise and sunset times (e.g., Geiger et al., 1995; Whiteman and Allwine, 1986; Whiteman, 1990; 2000; Barry, 2008). Measurements at multiple sites within individual valleys or basins have been reported by Whiteman et al. (1989a) from the northwest–southeast-oriented Brush Creek Valley, Colorado, by Matzinger et al. (2003) from the north-northwest–south-southeast-oriented Riviera Valley, Switzerland, and by Hoch and Whiteman (2010) from the nearly circular Meteor Crater, Arizona. Local sunrise and sunset times at unobstructed locations, such as ridgetop sites, are identical to astronomical sunrise and sunset times, while shadows cast by the surrounding topography and self-shading (i.e., the surface faces away from the sun) can delay local sunrise and advance local sunset considerably. For example, Matzinger et al. (2003) observed local sunrise on a west-facing slope 3.5 h after astronomical sunrise. Whiteman et al. (1989a), Matzinger et al. (2003), and Hoch and Whiteman (2010) report symmetric diurnal cycles of incoming solar radiation on flat surfaces (e.g., valley floors), with a peak at solar noon. East-facing and west-facing slopes, however, have a strongly asymmetric diurnal cycle, with their maximum in the morning and afternoon, respectively (Whiteman, 2000). The magnitudes of the respective peaks on the opposing sidewalls depend on the slope angle and the sun’s zenith angle. In the Riviera Valley, for example, larger magnitudes were observed on the west-facing sidewall than on the valley floor because of higher surface-normal irradiation on the sloping sidewall in the afternoon (Matzinger et al., 2003). Net radiation closely follows the diurnal cycles of incoming solar radiation, with morning and afternoon peaks on east- and west-facing slopes, respectively (Whiteman et al., 1989a; Matzinger et al., 2003; Hoch and Whiteman, 2010). On horizontal planes, on the other hand, the peak in net radiation may be shifted somewhat to an earlier time compared with incoming solar radiation because of higher surface temperatures and thus higher longwave outgoing radiation in the afternoon (Hoch and Whiteman, 2010).

Spatial variations in solar and net radiation within a valley lead to similar variations in the energy-balance components, including the surface-sensible and latent heat fluxes (Whiteman et al., 1989b; Whiteman, 1990; Rotach and Zardi, 2007). Whiteman et al. (1989b) report diurnal cycles from the northwest–southeast-oriented Brush Creek Valley applying a Bowen-ratio-based flux-partitioning method using measurements of net radiation, ground heat flux, and vertical profiles of temperature and water vapor pressure, while Rotach and Zardi (2007) report eddy-covariance measurements of diurnal cycles from the approximately north–south-oriented Riviera Valley. Both studies show that the diurnal cycles of the sensible heat flux closely follow the diurnal cycle of net radiation, with a shift of the sensible heat flux maximum from the morning at east-facing sidewalls over noon at the valley floor and unobstructed ridgetop sites to the afternoon at west-facing sidewalls. The flux magnitudes are influenced by the magnitudes in solar radiation, but also by the surface conditions and the partitioning into sensible and latent heat fluxes. In the Riviera Valley, the observed sensible heat flux maximum on the west-facing sidewall in the afternoon was much higher than the morning maximum on the east-facing sidewall, in agreement with the higher incoming radiation on the west-facing sidewall (Rotach and Zardi, 2007). Partitioning of available energy into sensible and latent heat fluxes strongly depends on moisture availability, with the latent heat flux being dominant over wet and vegetated surfaces (Oke, 2000).

Above variations in solar radiation and in the surface energy balance further cause the development of local microclimates and soil conditions. Comparisons of forest stands on north- and south-facing sidewalls have shown differences in the composition of the forests, number of different species, tree density, and timberline characteristics (Geiger et al., 1995; Paudel and Vetaas, 2014; Måren et al., 2015), and in agricultural use across valleys (Aulitzky, 1984; Oke, 2000; Barry, 2008; Wieser et al., 2009; Paudel and Vetaas, 2014). Spatial variations also impact and produce local thermally driven circulation systems. Variations in the onset of daytime upslope flows and up-valley flows have been found in observational data and in model results, with an earlier onset over sunlit sidewalls (Reiter et al., 1983; Anquetin et al., 1998; Colette et al., 2003; Lehner and Gohm, 2010), and across-valley differences in solar radiation can produce flow circulations across small valleys (Lehner et al., 2011; Lehner and Whiteman, 2012; Lehner, 2014).

A question that is still not entirely solved is the non-closure of the energy balance (Mauder et al., 2020), that
is, that the sum of the sensible and latent heat fluxes does not balance the available energy input from net radiation and the ground heat flux, resulting in residuals of about 10–35%, even over flat and homogeneous terrain (Oncley et al., 2007; Foken, 2008). While early explanations of the nonclosure were mainly based on potential measurement errors of the individual energy-balance components, recent findings show that the accuracy of state-of-the-art measurements is too high to explain the magnitudes of the residuals (Foken, 2008; Mauder et al., 2020). Current research suggests that the nonclosure is related to surface heterogeneities resulting in transport by large eddies that are not captured by traditional eddy-covariance analysis (Foken, 2008) and in quasi-stationary circulations causing advection (Mauder et al., 2010). In mountainous terrain, residuals may be even larger than over flat terrain (Rotach et al., 2008), where large surface heterogeneities exist and mesoscale circulations are a dominant feature. In addition, measurement design can play a bigger role than over flat terrain. For example, Wohlfahrt et al. (2016) found that net radiation measured parallel to the underlying surface over sloping terrain is better in phase with the sum of the sensible and latent heat fluxes compared with horizontal measurements, resulting in an improved energy-balance closure.

Comparatively little information is found about the exchange of momentum in mountainous terrain. It has been shown, however, that jet profiles associated with thermally driven flows and local terrain effects impact wind shear and thus momentum fluxes (Nadeau et al., 2013). For example, the increase and decrease of katabatic-wind speeds with height below and above the jet maximum, respectively, results in a downward momentum flux below the jet maximum, and an upward momentum flux above the jet maximum (Grachev et al., 2016; Stiperski et al., 2020). Stiperski et al. (2020) observed near-zero turbulent fluxes above the jet maximum because of strong stability damping turbulence. Directional wind shear has been suggested to cause vertical changes in momentum fluxes within the surface layer (Sfyri et al., 2018), where fluxes are otherwise expected to be near constant with height, and to increase turbulence complexity (Stiperski et al., 2019). Directional wind shear as a result of the interaction between shallow slope wind flows over valley sidewalls and the valley wind circulation aloft has also been shown to impact the lateral shear stress (Van Gorsel et al., 2003; Rotach et al., 2008). While this component is negligible over flat terrain, it can contribute significantly to the total shear stress over sloping valley sidewalls.

In this study, we present diurnal cycles of turbulent fluxes from six sites in the approximately southwest–northeast-oriented Inn Valley, Austria, for clear-sky, synoptically undisturbed, valley wind days (VWDs). The main objectives are:

1. to characterize the large spatial variations that can occur in the radiative and near-surface turbulent energy and momentum fluxes over relatively small horizontal scales in complex terrain due to variations in the local surface properties and wind conditions.
2. to demonstrate the large impact of the thermally driven wind circulations and their characteristic diurnal cycle on the temporal development of the turbulent fluxes.
3. to highlight that large deviations from flat-terrain observations typically found in textbooks can occur in the turbulent fluxes over complex terrain.
4. to demonstrate the differences between our observations in the east–west-oriented Inn Valley and observations from north–south-oriented valleys described in previous publications.

The measurement sites, the dataset, and the processing methods are described in Section 2. Spatial variations in the diurnal cycles of the turbulent fluxes and their forcing processes are discussed in Section 3, while vertical variations in the diurnal cycles of turbulent fluxes are presented in Section 4. Finally, results are discussed and summarized in Sections 5 and 6, respectively.

2 | DATA AND DATA PROCESSING

2.1 | Measurement sites

The i-Box (Innsbruck Box) project was designed to study the turbulence structure in complex, mountainous terrain (Rotach et al., 2017). Long-term eddy-covariance measurements are thus being made at six sites within the Inn Valley in the western part of Austria. The Inn Valley runs approximately southwest–northeast and opens north to the German Alpine Foreland near Kufstein (Figure 1a). The six i-Box stations are located within an approximately 6.5-km long section of the valley about 20 km east of Innsbruck. In the vicinity of the measurement sites, the valley floor is approximately 2 km wide and the surrounding mountains extend about 2,000 m above the valley floor.

The measurement sites were selected to represent different topographic (i.e., slope angle and orientation) and land-use characteristics (Figures 1b, 2 and Table 1). The valley floor site (VF0) constitutes a reference site, as it is located on the almost flat valley floor. The 17-m high tower is instrumented with sonic anemometers at three vertical levels and fast-response hygrometers at two levels. The site is mainly surrounded by mixed agricultural
Figure 1  (a) Location of the i-Box measurement installation within the Austrian Inn Valley indicated by the square east of Innsbruck, which outlines the domain of (b), and (b) detailed view of the i-Box measurement sites. Elevation contour lines in (b) are every 100 m. Dashed lines in (b) indicate the orientation of the valley axis in three sections of the valley labeled (i)–(iii). Site labels and characteristics are described in Table 1 [Colour figure can be viewed at wileyonlinelibrary.com]

fields. Two sites are located on the south-facing sidewall, with one site only 30 m above the valley floor (SF8). The station is located next to a small embankment at the edge between a concrete helicopter landing zone and agricultural land. The 12-m high tower is instrumented with sonic anemometers at two levels and a fast-response hygrometer at the top level. The second south-facing site SF1 is located at an almost flat plateau in the lower part of the north valley sidewall, surrounded by grassland and agricultural fields. The two sites on the north-facing sidewall are located at somewhat steeper slopes of 11° (NF10) and 25° (NF27), with the vegetation at both sites being mainly grassland. The sixth site is a mountain-top station (MT21), which is located slightly below ridgetop on a steep and narrow west-facing slope, with the terrain dropping off to the north and south of the slope. However, as the main wind directions at MT21 are northerly and southerly (see Section 3.2), so that the most important footprint areas include north-facing and south-facing terrain (Figure 2), the site is classified as a mountain-top site for the purpose of radiation calculations. Sites SF1, NF10, NF27, and MT21 are all equipped with one sonic anemometer and a fast-response hygrometer at 4.7–6.8 m above ground level (AGL). In September 2017, a second sonic anemometer was installed at NF27, at 1.5 m AGL.

All fast-response measurements are made with a sampling frequency of 20 Hz. Wind components are measured with CSAT3 sonic anemometers (Campbell Scientific Ltd., Logan, Utah, USA), with the exception of MT21 where a uSonic3 sonic anemometer (METEK Meteorologische Messtechnik GmbH, Elmshorn, Germany) is installed. An open-path, infrared gas analyzer (EC150, Campbell Scientific Ltd.) is operated at the lowest level of VF0 and, since September 2017, at NF27. All other fast-response hygrometers are Krypton hygrometers (KH20, Campbell Scientific Ltd.). Air temperature and humidity measurements used for flux corrections (Section 2.2) come from additional PT100 temperature and HT-1 humidity sensors (HC2A-S, Rotronic, Basserdorf, Switzerland) installed at all sites. Additional profiles of temperature and humidity are measured at VF0 since July 2018, with sensors (HC2A-S, Rotronic, Basserdorf, Switzerland) located at 2, 4, 8.7, and 16.9 m AGL. Four-component radiation is measured with CNR4 net radiometers (Kipp & Zonen, Delft, The Netherlands) at NF10, NF27, and MT21 and a combination of CMP21 pyranometers and CGR4 pyrgeometers (Kipp & Zonen, Delft, The Netherlands) at VF0. Radiation sensors are installed parallel to the sloping terrain at NF27 and horizontal at VF0, NF10, and MT21. Soil instrumentation includes heat flux plates at depths of 10 cm (HFP01, Hukseflux, Delft, The Netherlands) and temperature and moisture probes a few centimeters above the heat flux plates (TRIME-PICO, IMKO, Ettlingen, Germany). Further details about the instrumentation used at the i-Box stations can be found in Rotach et al. (2017) and their supplemental information.

2.2  Data processing

The analysis focuses on synoptically undisturbed, clear-sky days, or so-called valley wind days (VWDs), during 2014–2019, with the exception of MT21, which has only been operational since October 2014. During VWDs, we expect the largest terrain-induced spatial differences in solar irradiation affecting turbulent exchange and the wind field being dominated by the valley wind circulation in the absence of large-scale pressure gradients.
The identification of the VWDs is based on Lehner et al. (2019), who used ERA Interim reanalysis data to classify synoptically undisturbed conditions. Since the ERA Interim reanalysis was discontinued in summer 2019, the method described in Lehner et al. (2019) was applied to ERA5 data. Because of the higher resolution of ERA5 compared with ERA Interim, small modifications were necessary, which included smoothing the geopotential height fields three times with a 5x5 grid point box average and calculating gradients across $6\Delta x$, which is the same distance as $2\Delta x$ used by Lehner et al. (2019) for ERA Interim data. The classification yields a total of 74 VWDs during the 6 years (Table 2), which corresponds to about 3.4% of all days. Table 2 also shows that the number of VWDs is not distributed evenly throughout the year, but that the highest number of VWDs occurs in summer and fall, with 29 VWDs between June and August and 26 VWDs between September and November compared with 9 VWDs between March and May and 10 VWDs between December and February. This means that, depending on data availability, mean diurnal cycles discussed in the remainder of this paper contain about three times as many summer days as winter days.

Turbulent fluxes and other turbulence statistics are calculated from the 20-Hz data of the sonic anemometers and fast-response hygrometers using EdiRe Data Software (Clement, 1999). Data processing is largely guided by Stiperski and Rotach (2016), who tested several processing options for the i-Box dataset, including different data filtering options, averaging intervals, and coordinate rotations. The data are thus despiked and filtered using a high-pass recursive filter with a time scale of 200 s, and velocity components are rotated into a streamline coordinate system using double rotation (McMillen, 1988; Aubinet et al., 2012) before turbulence statistics are calculated over 30-min averaging intervals. Several corrections...
Table 1: Site characteristic, elevation, local slope orientation, local slope angle, turbulence measurement levels, temperature measurement levels, and availability of radiation and soil measurements at the six i-Box stations

| Site | Site characteristic | Elevation (m) | Local slope orientation | Local slope angle (°) | Turbulence heights (m) | Temp. height (m) | Radiat./soil |
|------|---------------------|--------------|-------------------------|----------------------|------------------------|-----------------|--------------|
| VF0  | Valley floor        | 545          | Flat                    | 0                    | 4.0, 8.7*, 16.9        | 16.9           | Yes          |
| SF8  | South-facing sidewall| 575          | South-southeast         | 9                    | 6.1*, 11.2             | 11.2           | No           |
| SF1  | South-facing sidewall| 829          | East-northeast          | 3                    | 6.8                    | 6.2            | No           |
| NF10 | North-facing sidewall| 930          | Northwest               | 11                   | 5.7                    | 5.6            | Yes          |
| NF27 | North-facing sidewall| 1,009        | North                   | 25                   | 1.5*, 6.8              | 6.7            | Yes          |
| MT21 | Mountain top        | 2,015        | Flat site on west-facing slope | —                    | 4.7                    | 4.0            | Yes          |

Note: Measurement levels with a sonic anemometer, but without a fast-response hygrometer, are indicated by asterisks.

*Site names are identical to Rotach et al. (2017) and other i-Box publications, with the last digits referring to an earlier assessment of the local slope angles.

Local slope orientation and slope angle were determined from a 10-mdigit elevation model (data source: Land Tirol—data.tirol.gv.at) that was smoothed by a 10 × 10 grid box average (100 m × 100 m).

Since September 2017.

Table 2: Number of VWDs per month and year

|       | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Annual |
|-------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|--------|
| 2014  | 0   | 0   | 1   | 1   | 0   | 2   | 1   | 0   | 3   | 1   | 1   | 0   | 10     |
| 2015  | 0   | 1   | 0   | 1   | 0   | 2   | 2   | 3   | 1   | 0   | 0   | 2   | 12     |
| 2016  | 0   | 0   | 1   | 0   | 0   | 2   | 0   | 4   | 7   | 0   | 0   | 3   | 17     |
| 2017  | 2   | 2   | 0   | 0   | 3   | 1   | 0   | 0   | 5   | 0   | 0   | 13  |
| 2018  | 0   | 0   | 0   | 2   | 0   | 2   | 7   | 1   | 7   | 0   | 0   | 0   | 21     |
| 2019  | 0   | 0   | 0   | 0   | 1   | 0   | 0   | 0   | 0   | 0   | 0   | 1   |
| 2014–19 | 2  | 3   | 2   | 4   | 3  | 10  | 5   | 14  | 12  | 13  | 1   | 5   | 74     |

are applied to the fluxes (Aubinet et al., 2012), including frequency response corrections (Moore, 1986), humidity corrections for the sensible heat flux (Schotanus et al., 1983), and density (Webb et al., 1980) and oxygen (van Dijk et al., 2003) corrections for the latent heat flux. No corrections are applied to horizontal heat fluxes.

Stiperski and Rotach (2016) define two sets of quality criteria, specifically, low and high quality. The low-quality control includes checks for instrument diagnostic flags and malfunctioning, as well as threshold values for skewness and kurtosis of temperature and wind components following Vickers and Mahrt (1997). The high-quality control includes additional checks for stationarity following Foken and Wichura (1996) and uncertainty based on Wyngaard (1973). Here, we use much less stringent quality criteria. Since diurnal cycles of multiple days are averaged, too stringent quality criteria and thus unavoidable gaps in the data could lead to biases in the averaged diurnal cycles. For example, if many data points are excluded during the morning transition period because of nonstationarity, the remaining data points during this period may not be equally distributed throughout the year compared with the rest of the diurnal cycle. The simple quality criteria used herein include the removal of data when any of the 20-Hz raw data in an averaging interval are missing or when more than 10% have to be excluded due to instrument diagnostics, spike removal, or exceeding of physical limits and when the above described flux corrections cannot be performed correctly because of missing or faulty standard meteorological measurements. In addition, sensible and latent heat flux values larger than 700 W·m⁻²; wind speed and direction values for wind speeds larger than 50 m·s⁻¹; momentum fluxes, TKE, and velocity variances larger than 10 m²·s⁻²; and occasional spikes in the time series (i.e., data points that exceed their immediate neighbors by 50 W·m⁻² for heat fluxes, 5 m·s⁻¹ for wind, and 1 m²·s⁻² for momentum fluxes and velocity variances) were excluded. The above threshold values were selected subjectively based on the dataset. For soil moisture and temperature, which have smoother diurnal cycles, data points were removed when they exceeded two times a moving 6-hr standard deviation.
After removing data that do not pass quality control, data gaps of less than 2 hrs were linearly interpolated, and all resulting complete days are used for further analysis.

To make days from different seasons comparable and allow for a meaningful averaging of short winter days with low magnitudes of turbulent fluxes and long summer days with large magnitudes, both time and fluxes are normalized. Radiation components and heat fluxes are normalized with the maximum solar radiation at the top of the atmosphere at the location of VF0 on a given day. While this normalization with solar radiation at VF0 removes seasonal variations, it maintains the spatial variations among the different sites, which are the focus of this work. Turbulence kinetic energy (TKE), friction velocity \( u_* \), momentum fluxes, and wind-component variances are normalized with \( \Sigma R_{TOA}/(0.5M_0\rho_0) \), where \( \Sigma R_{TOA} \) is the total daily solar irradiation in \( J \cdot m^{-2} \) at the top of the atmosphere at VF0, \( \rho_0 = 1.0 \, kg \cdot m^{-3} \) a reference density, and \( M_0 = 2,000 \, m \) a reference valley depth representative of the topography surrounding the i-Box measurement location. The above normalization factor is proportional to the forcing for the valley wind circulation due to differential heating of the valley and the adjacent plain based on the valley volume effect (Whiteman, 2000). As stronger radiative forcing in summer leads to stronger valley winds and thus higher TKE and momentum fluxes, the normalization factor reduces these seasonal effects. Similarly, air temperature is normalized with \( \Sigma R_{TOA}/(0.5M_0\rho_0c_p) \), where \( c_p \) is the specific heat at constant pressure. Before this normalization, the mean daily temperature at VF0 is subtracted from the diurnal cycle of temperature at all stations to remove day-to-day variations resulting from different air masses, which affect temperature in addition to seasonal effects. All normalized parameters are indicated by an asterisk; for example, the normalized sensible heat flux is termed \( H^* \). Time is normalized with respect to astronomical sunrise and sunset times at VF0, so that sunrise corresponds to \( t^* = -1 \), solar noon to \( t^* = 0 \), and sunset to \( t^* = 1 \). The analysis of nighttime periods is limited to the periods immediately before sunrise and after sunset, since this normalization is not designed for nighttime data. Short winter days with noon at 1200 UTC and sunset at 1600 UTC would lead to \( t^* = 3 \) at midnight, whereas long summer days with sunset at 2000 UTC would lead to \( t^* = 1.5 \) at midnight. After normalizing the time, which leads to time intervals that vary from day to day, the data are interpolated to a regular time vector with a time step of \( \Delta t^* = 0.1 \) before calculating medians and interquartile ranges. While all of the presented analysis is based on median diurnal cycles, arithmetic means were calculated as well for major parameters and compared with the medians. The differences between the two do not lead to qualitative changes in the results. All individual diurnal cycles used to calculate medians are available from the i-Box Wiki page\(^1\) for most of the variables discussed in this manuscript, but without normalization, that is, with only time being normalized. In addition to the median diurnal cycles calculated over the whole dataset, seasonal medians are presented in the online supporting information, Appendix S1.

## Ground heat flux

Soil measurements are performed at four sites (Table 1). The ground heat flux is the sum of the measured ground heat flux at about 10 cm below ground \( G_{10} \) and the storage term in the layer above (Foken, 2017): 

\[
G(t_i) = G_{10}(t_i) + \frac{C_G \Delta \zeta [T_s(t_{i+1}) - T_s(t_i)]}{t_{i+1} - t_i},
\]

where \( t \) is time, \( T_s \) the instantaneous soil temperature at the end of each half-hour averaging period measured at about 5 cm below the surface, and \( C_G \) the heat capacity of the ground

\[
C_G = \rho_s c_s (1 - m_s) + \rho_w c_w m_s,
\]

with \( m_s \) the soil moisture content measured at about 5 cm below the surface and \( \rho_w = 1,000 \, kg \cdot m^{-3} \) and \( c_w = 4,190 \, J \cdot kg^{-1} \cdot K^{-1} \) the density and specific heat of water, respectively. The specific heat of the dry soil \( c_s = 800 \, J \cdot kg^{-1} \cdot K^{-1} \) was taken from Arya (2001) assuming sandy soil and the density of the dry soil \( \rho_s = 1,120 \, kg \cdot m^{-3} \) is based on a single soil sample from VFO. Arya (2001) lists a dry-soil density of 1,600 kg-m\(^{-3}\) for sandy soil.

## Spatial Variations in the Diurnal Cycles of Turbulent Fluxes

### Radiation

The surface energy budget is strongly driven by solar radiation during VWDs. To get an overview of radiative forcing at the six sites, the solar incidence angle is shown as a function of time of day and day of the year in Figure 3. The calculation of the solar incidence angle does not take shading by the surrounding topography into account, which may further reduce solar radiation, particularly around

\(^{1}\)https://wiki.ubik.ac.at/download/attachments/755466281/Supplement_AllDays_NotNormalized.pdf?version=1&modificationDate=1598874982768&api=v2
FIGURE 3  Solar incidence angle at the six i-Box sites as a function of time of day and day of the year (DOY). Calculations are based on local slope angles (Table 1) [Colour figure can be viewed at wileyonlinelibrary.com]

sunrise and sunset. Incidence angles at the valley floor site, the unobstructed mountain-top site, and the two low-angle sites facing south are relatively similar, with maximum incidence angles in summer of more than 65°. The largest reductions in solar radiation occur on the north-facing sites, particularly at the steep site NF27, which has much lower incidence angles throughout the year, with a peak value just above 40°, and which does not receive any direct solar radiation during the winter months.

Radiation measurements are only available at four of the six sites, with no routine measurements on the two south-facing sites. The median diurnal cycles of the four radiation components, net radiation, and albedo are shown in Figure 4. Days with a peak albedo of more than 0.9 were removed from the analysis, as this likely indicates snow or dirt on the upward-facing radiometers. The radiation sensors are mounted slope-parallel at NF27, but horizontal at the other three sites, with the underlying terrain being flat at VF0 and MT21. To give an indication of the diurnal cycle of the radiation budget over the sloping surface at NF10, the total shortwave incoming radiation was converted using

$$S_{slp} = S_{hor} \frac{\cos i}{\cos \zeta}, \quad (3)$$

where $S_{slp}$ is the direct solar radiation over a sloping surface, $S_{hor}$ the horizontally measured direct solar radiation, $i$ the angle between the solar beam and the slope-normal direction, and $\zeta$ the sun’s zenith angle. Since direct and diffuse solar radiation are not measured separately at the i-Box sites, this will thus lead to a small underestimation as diffuse radiation is also reduced. Net radiation was calculated on the basis of both horizontally measured and slope-parallel shortwave incoming radiation.

As already indicated by the solar incidence angle, the magnitudes of incoming solar radiation are very similar at all sites except NF27 (Figure 4a), as expected for low slope angles (e.g., Whiteman, 2000). The MT21 site is somewhat complex because of its location on a long west-facing, sloping ridge, which drops off to the north and south. As the radiation sensor is mounted horizontally, parallel to a small area of almost flat ground where the station is located, the observed radiation peaks around noon. Slightly increased variability (indicated by the interquartile range in Figure 4) at MT21 is likely a result of spatially confined clouds over the mountain during daytime, which are not present over the valley and thus do not affect the identification of clear-sky days at VF0. NF10 shows also somewhat higher variability after sunrise, which is mostly due to winter days, when local sunrise is delayed considerably at the site to shortly before solar noon. Despite the normalization, seasonal variations exist in the diurnal cycles of radiative and turbulent fluxes, which may be masked when averaged over all available VWDs throughout the year. To illustrate these seasonal differences, the median diurnal cycles for the winter, spring, summer, and fall months are shown in Figure S2 of the online supporting information, Appendix S1. The steep north-facing site has overall much lower incoming radiation compared with the other sites during all seasons and does not receive direct solar radiation at all in winter, which also leads to a large interquartile range throughout the day. The
FIGURE 4 Median diurnal cycles of normalized (a) shortwave incoming radiation $SW_{in}^*$, (b) shortwave reflected radiation $SW_{out}^*$, (c) longwave incoming radiation $LW_{in}^*$, (d) longwave outgoing radiation $LW_{out}^*$, (e) net radiation $R_{net}^*$, and (f) albedo $\alpha$ at the four sites with radiation measurements (Table 1). Subscripts in the top legend indicate the orientation of the sensor (h, horizontal; gp, ground parallel) and the subscript ‘c’ in NF10$^{gp,c}$ indicates that the respective components are based on a conversion of $SW_{in}^*$ using Equation 3. Time is normalized with respect to astronomic sunrise and sunset times at VF0, and radiation components are normalized by the daily maximum solar radiation at the top of the atmosphere at VF0. Shading indicates the interquartile range. The small color arrows at the top show the median of the times of maximum insolation on sloping plains with the same slope angle and aspect as the respective sites. The numbers in the legend of (a) indicate the total number of complete diurnal cycles available for averaging at the respective sites [Colour figure can be viewed at wileyonlinelibrary.com]

The effect of slope exposure at NF27 was shown by a short, 1-week comparison of slope-parallel and horizontal measurements with two additional four-component radiation sensors in April 2017. Two days with little cloud cover are shown in Figure S3a in the online supporting information, Appendix S1.

Slightly higher spatial variations occur in the reflected shortwave radiation (Figure 4b) and thus in the calculated surface albedo (Figure 4f). The highest albedo in the morning is observed at the flat valley-floor site throughout the year, consistent with findings by Whiteman et al. (1989a). The diurnal cycles of albedo at VF0 and NF10 also follow the observations by Hoch and Whiteman (2010), with the highest values in the morning and evening, when the sun’s elevation angle is lowest. It must be noted, however, that the variability is generally strongest in the morning and evening at all sites, probably as a result of shading during the winter months. While MT21 shows a
similar increase in albedo in the evening, it has a minimum in the morning, even during the summer months (Figure S1e). The morning minimum may be related to the station’s location on a west-facing slope that leads to reduced reflectance from the terrain surrounding the sensor. NF27 has a completely different diurnal cycle, with a continuous increase in albedo throughout the whole day and overall much higher values compared with the other sites, although the land use at NF27 does not differ significantly from that at the other sites. Matzinger et al. (2003) observed similar diurnal cycles, with an increase throughout the day for horizontal measurements over west-facing sloping terrain due to anisotropic reflectance, but not for slope-parallel measurements as at NF27.

Longwave incoming radiation is lowest at MT21, while values at the other sites are relatively similar. The reduced radiation is likely a combination of decreasing air temperature (Figure 5) and humidity with height compared with the valley sites and the unobstructed location at the mountain top. Valley sites have a reduced sky-view factor with, for example, 97% and 95.7% at VF0 and NF27, respectively, compared with 99.7% at MT21 (Graf 2017, unpublished BSc thesis), so that they will also receive longwave radiation from the surrounding topography, which has a higher emissivity than air and is partially warmer. A difference occurs during the winter months, when longwave incoming radiation in the morning is on average lower at VF0 than at NF10 and NF27 (Figure S2c), likely due to the frequent occurrence of temperature inversions in the valley and more frequent snow cover on the slopes and thus the coldest surface temperatures near the valley floor. Air temperature observations show the occurrence of deep morning inversions in winter that extend to crest height, with median temperatures at VF0 and SF8 being lower than at MT21 (not shown), whereas MT21 remains colder at night than the valley sites during the rest of the year (Figure 5). A shallower nighttime inversion can, however, be also found throughout the year, with median morning temperatures at VF0 and SF8 lower than at the other valley sites, as seen in the annual median diurnal cycles. It has to be kept in mind, however, that temperature is not measured at the same height above ground at all of the sites (Table 1), so that valley-scale temperature gradients cannot be strictly separated from near-surface temperature gradients and local microclimate effects.

Longwave outgoing radiation reflects the mean surface temperatures at the sites, with somewhat lower median values at MT21, which are mostly due to the summer months, when the mountain-top temperatures are lower than in the valley (Figure S2d). Low daytime values at NF27, on the other hand, are mainly due to days during fall and winter, when the site is mostly shaded. During the winter months, the lowest nighttime values occur again at VF0, at the bottom of the valley inversion. Both longwave incoming and outgoing radiation have a relatively high interquartile range (Figure 4c–d) as a result of a few winter days with large normalized longwave fluxes.

The relative lack of spatial variations in net radiation (with the exception of NF27) is a result of incoming solar radiation, with the variations in the other components having comparatively little impact on net radiation (Figure 4e). This dominant influence of incoming solar radiation on net radiation is similar to observations in previous studies (e.g., Whiteman et al., 1989a; Matzinger et al., 2003; Hoch and Whiteman, 2010). These studies, however, found relatively large differences between opposing sidewalls, as their measurements were being taken on east- and west-facing sidewalls in contrast to the north- and south-facing sidewalls in the west–east-oriented Inn Valley. While no routine radiation measurements are made on the south-facing sidewall, a four-component radiation sensor was deployed at SF1 for 1 week in April 2017. Unfortunately the period was mostly cloudy, but the four radiation components are shown in Figure S3b in the online supporting information, Appendix S1 together with measurements from an additional horizontally installed radiation sensor at NF27 for 1 day that was mostly cloud free until the afternoon. While the incoming solar radiation measured by the two horizontal sensors is almost
the same on the north- and south-facing sidewalls, the converted slope-parallel component is reduced at NF27 compared with the almost flat SF1 site.

3.2 Valley wind circulation

The wind field during VWDs is, of course, characterized by the valley wind circulation. The median wind speed and wind direction are shown in Figure 6 together with the expected up-valley and down-valley wind directions based on the orientation of the valley axis and the upslope and downslope directions at SF8, NF10, and NF27. Slope wind directions are based on the slope orientation of the sites listed in Table 1. The valley axis bends slightly at the location of the i-Box sites, with an orientation of about 70° up-valley of VF0 and about 40° down-valley (Figure 1b).

Before sunrise, the wind is generally from a south-westerly down-valley direction at VF0 and SF1, with more southerly downslope directions on the north-facing sites NF10 and NF27 (see also Stiperski and Rotach, 2016) and a northerly downslope component at SF8. SF1 is located at a plateau that slopes slightly downwards to the northeast, so that the downslope direction coincides with the down-valley direction. Based on wind direction, it is thus not possible to separate between downslope and down-valley winds. Wind speeds are generally low before sunrise, that is, at or below 1 m·s⁻¹, with the exception of MT21, SF1, and the 1.5-m level at NF27. Shallow downslope flows at NF27 likely result in a jet-like wind-speed profile with a near-surface maximum (Stiperski et al., 2019). SF1 typically shows much higher nighttime wind speeds than the other valley sites. Daily radiosoundings performed at 0300 UTC at Innsbruck Airport, approximately 20 km west of the i-Box measurement sites, give an indication of the nighttime vertical wind profiles during VWDs (Figure 7). The orientation of the valley axis near Innsbruck is more west–east than at the location of the i-Box sites (Figure 1). The down-valley flow has thus a more westerly direction (Figure 7c). It extends to about 1,500 m MSL with a nearly constant valley-parallel wind direction and a jet-like profile. The median jet maximum occurs at about 400 m above the valley floor, near the top of an approximately isothermal layer (Figure 7a), with wind speeds between 1.5 and 5 m·s⁻¹ and a median of about 3 m·s⁻¹ (Figure 7b). The jet maximum is thus close to the elevation of the SF1, NF10, and NF27 sites. While the observed flow at the north-facing sites and at SF8 is mostly determined by downslope winds before sunrise, the observed high wind speeds at SF1 suggest that the wind field at the plateau is dominated by the down-valley flow. Comparing the median wind speeds at SF1 (Figure 6) with the wind speeds in the Innsbruck radiosounding at the same elevation (Figure 7), a down-valley flow acceleration is visible. Aside from a possible change in the elevation of the jet maximum or a general acceleration of the
down-valley flow between Innsbruck and the i-Box sites farther downstream, it is also possible that the speed-up is a result of the plateau in the terrain, similar to observed flow accelerations over escarpments (e.g., Emeis et al., 1995). The location of MT21 on a narrow west-facing slope that drops off to the north and south somewhat complicates the interpretation of the observed wind field. The pronounced southerly component at MT21 (Figure 6b,e) could be influenced by the large-scale flow at crest height, but could also suggest that the down-valley flow extends to above 2,000 m MSL and thus to MT21 in this part of the valley. A similarly deep down-valley flow was observed in a morning profile near Innsbruck by Vergeiner and Dreiseitl (1987), while nighttime radiosounding profiles from Innsbruck Airport suggest, however, a lower median down-valley flow depth.

With sunrise, the wind direction remains down-valley at VF0 and SF1, and with the weakening of the downslope winds, the wind direction also shifts to a down-valley direction at SF8 and NF10, except for in the winter months, when downslope flows continue throughout the day at NF10 (Figure S2g). The wind speed increases at the valley floor and at SF8 to reach a first maximum between sunrise and solar noon, presumably due to a downward transport of momentum in the deepening boundary layer. Wind speeds at these two sites thus approach the observed wind speed at SF1, corresponding to the jet maximum wind speed of the nocturnal down-valley winds. The median morning maximum in wind speed is reached shortly after the break-up of the valley inversion (Figure 5), which marks the change in thermal valley-wind forcing from down-valley to up-valley. As the forcing for down-valley winds decreases, wind speed weakens again and reaches a minimum around solar noon, when the wind direction changes to an up-valley direction at most sites. The higher pre-sunrise wind speeds at SF1 continue until mid-morning, when wind speeds at VF0 and SF8 have reached similar magnitudes and wind speeds at SF1 start to decrease together with VF0 and SF8.

The behavior on the north-facing sidewall differs somewhat, as both NF10 and NF27 do not show pronounced diurnal cycles in wind speed in the morning, but rather low wind speeds, which continue throughout the day at NF27. This is likely due to the fact that these sites are less influenced by the valley wind circulation, but more by local slope winds as indicated by the wind direction. At NF27, a northerly upslope flow develops in the median wind field after sunrise, except for in winter, when downslope winds continue throughout the day (Figure S2g).

The noon transition occurs almost simultaneously at VF0, SF1, and NF10 on average, with a slightly delayed transition at SF8 (Figure 6d). There are, however, seasonal differences, with a generally later transition during winter that occurs only in mid-afternoon (Figure S2g). After the flow transition, the wind speed increases again to reach a maximum in the afternoon between noon and sunset at the valley sites, but with large interquartile ranges, which are a result of seasonal effects. In contrast to the morning maximum, which reaches similar magnitudes throughout the year, the afternoon maximum varies considerably with peak median values of 1–2 m s\(^{-1}\) in winter to values of 3.5 to over 5 m s\(^{-1}\) in summer at most sites. It has already been shown by Vergeiner and Dreiseitl (1987) that the up-valley wind period is longest and wind speeds are highest in summer and fall in the Inn Valley. The weakening of the up-valley winds starts before sunset, but the transition to the nighttime down-valley regime happens on average after sunset at VF0 and the south-facing sites, when wind speeds decrease again to about 1 m s\(^{-1}\) or less. At NF10, the transition from up-valley to down-slope flows occurs somewhat earlier, that is, already in the late afternoon. At NF27, the transition is more continuous. At MT21, the wind direction starts to transition to a
north-easterly direction in mid-morning, which lasts until after sunset. The variability in wind direction is, however, relatively large in the early afternoon, which indicates that a southwesterly wind direction may continue at MT21 until later in the afternoon or even throughout the day in winter despite an earlier flow transition in the valley (Figure S2g). The diurnal cycle of wind direction at the station does not show local upslope winds on the west-facing slope. The brief southwesterly component during the noon transition could be related to upslope flows on the southwest-facing slope immediately south of the station. Wind speeds remain low at about 2 m\(\cdot\)s\(^{-1}\) until late afternoon, when a pronounced peak occurs around sunset. In winter, wind speeds are, however, larger than in the valley throughout most of the day, suggesting that the flow at MT21 is decoupled from the flow within the valley. When looking at seasonal differences, it has to be kept in mind, however, that for some parameters only a very small number of days is available for analysis, particularly during winter and spring. For example, only 3 days go into the winter median wind speed at MT21.

3.3 Energy fluxes

Diurnal cycles of normalized latent heat flux \(LE^\ast\) and sensible heat flux \(H^\ast\) are shown in Figure 8a–c together with the Bowen ratio calculated from the fluxes, that is, \(\beta = H^\ast/LE^\ast\). The sensible heat flux is generally smaller than the latent heat flux by a factor of about two to three, which
is also visible in the Bowen ratio, with values below 1. Similar values of $\beta$ were also shown by Vergeiner and Dreiseitl (1987) for a site near Innsbruck. The highest values of $\text{LE}'$ and thus the lowest Bowen ratios $\beta$ are observed at VF0, a site that is mostly surrounded by agricultural fields. This may be related to higher soil moisture at the partly irrigated farmland. $H^*$ and thus $\beta$ are highest at the south-facing site SF8. SF8 is also located at the edge of a concrete surface, which is contained within the afternoon footprint (Figure 2). Both $H^*$ and $\text{LE}'$ are much lower at the steep north-facing site NF27 than at the other sites, which is mostly due to the effect of shading and thus the strongly reduced available energy during most of the year. During the summer months, magnitudes similar to that of the other sites can be observed (Figure S2h,j). In contrast to the other valley sites, the north-facing sites NF10 and NF27 do not show a distinct diurnal cycle in $H^*$ during the winter months either. The magnitude and diurnal cycle of $H^*$ at MT21 differ strongly from the valley sites, with a large maximum in the afternoon, but before the occurrence of the peak in the median wind speed (Figure 6b). Note that the median diurnal cycle of the sensible heat flux at MT21 in Figure 8b has been multiplied by a constant factor of 1/3 to show it on the same axes as the other stations. The large difference in magnitude compared with the other sites could indicate the impact of advective processes or a lack of soil moisture. Unfortunately, no complete diurnal cycles of $\text{LE}'$ are available at MT21 during VWDs.

The sensible heat flux changes sign during the first half of the morning, on average somewhat later than the initial increase in $\text{LE}'$. The transition from negative nighttime to positive daytime values of $H^*$ occurs generally first at SF8 and VF0, followed by SF1 and NF27, NF10, and finally MT21. At the north-facing sites, the median $H^*$ remains negative or close to zero throughout the day in winter (Figure S2i). In contrast to observations in north–south-oriented valleys (Whiteman et al., 1989b; Rotach et al., 2008), there is little systematic difference in the timing of the $\text{LE}'$ and $H^*$ maxima between the north- and south-facing sidewalls. The median maximum in $\text{LE}'$ occurs in the early afternoon, both with respect to solar noon at VF0 and to local noon, except for NF10. At NF10, the peak agrees relatively well with the time of local noon, which occurs somewhat later than at the other valley sites. In winter, only a very weak maximum is reached late in the day at NF10 (Figure S2h). The maximum in the median $H^*$, on the other hand, occurs generally earlier, either before (VF0, SF1, and NF27) or around (SF8 and NF10) solar noon. The exception is MT21, where a pronounced maximum occurs in the afternoon, with values about three times as high as at the valley sites. The large magnitudes suggest that nonlocal effects play a significant role. The small difference in the timing of the maxima in $H^*$ and $\text{LE}'$ at the valley sites is also reflected in the Bowen ratio, which generally decreases throughout the day. A similar difference in timing with a maximum in $\text{LE}'$ past solar noon was also shown by Vergeiner and Dreiseitl (1987), and a decrease of the Bowen ratio was observed by Rott (1979) for a mountain grass site in western Austria, which was determined from measured temperature and humidity gradients from the energy balance closure using additional radiation and soil measurements.

The sensible heat flux generally reverses sign in the middle of the afternoon to reach a minimum value before sunset, after which it slowly returns to approximately zero. When $H^*$ reverses sign, the Bowen ratio also drops below zero. The final return of $H^*$ to very weakly negative values occurs simultaneously with the return to close-to-zero nighttime values in $\text{LE}'$ and coincides with the time when the daytime up-valley wind transitions back to a down-valley flow and wind speeds drop to low nighttime values below 1 m·s⁻¹ (Figures 6 and 8). The magnitude of the $H^*$ minimum around sunset has a seasonal cycle, with larger negative values in spring and summer (Figure S2i). While $H^*$ reverses sign first at SF8 in the morning, the transition back to negative values in the afternoon occurs last at SF8, so that SF8 has not just the largest magnitudes of $H^*$ but also the longest period with positive values on average. At the other valley sites, the evening sign change follows approximately the same order as the morning sign change, starting at VF0 and ending at NF10. In contrast to the afternoon minimum in $H^*$ at the valley sites, MT21 has a pronounced afternoon maximum and the median sensible heat flux reverses sign only around sunset.

Four of the i-Box sites are full surface-energy-balance stations (Table 1). Data coverage at MT21, however, is reduced, so that no full diurnal cycles of $\text{LE}'$ are available for VWDs. The normalized surface energy balance is thus only shown for VF0, NF10, and NF27 (Figure 9). Only a limited number of VWDs exists, for which full diurnal cycles of all four components are available, with 6, 19, and 10 days at VF0, NF10, and NF27, respectively. At all three sites, net radiation is balanced by $\text{LE}'$ to a relatively large extent, particularly during the afternoon, when the residual thus becomes small, except for NF10. This differs from other studies that have found the lowest closure during convective conditions (e.g., Stoy et al., 2013). With respect to NF10, it has to be kept in mind that radiation is with respect to a horizontal surface, which may add to the imbalance (Wohlfahrt et al., 2016). Because of the delay in the peak of $\text{LE}'$ compared with radiation, the residual peaks in the morning. The ground heat flux $G^{*}$ has a similar magnitude as the sensible heat flux at all three sites. Its change of sign in mid-morning and its afternoon peak, which occurs at about the same time or somewhat later than the peak in $\text{LE}'$, further contribute to the decrease in
FIGURE 9  Normalized energy-balance components at (a) VFO, (b) NF10, and (c) NF27, where $H^*$ and $LE^*$ are defined negative if directed upwards, that is, opposite to all other figures. Dashed lines are median values for all available VWDs, with the number indicated in the legend. Solid lines and shading show the median and interquartile range for VWDs, for which all components are available. The number of these days is indicated in the legend entry for the residual (res). $|res^*/R^*|$ shows the ratio between the residual and net radiation, with the horizontal dashed line indicating 100%. The energy balance ratio (EBR, Equation 4) is indicated in the top right corner [Colour figure can be viewed at wileyonlinelibrary.com]

The residual. The largest nonclosure in terms of the ratio between the residual and net radiation occurs, however, during the morning and evening transition periods when net radiation changes sign, as also mentioned by Mauder et al. (2020). This may be related to a lag in the response of the heat fluxes to the radiation budget. The residual and nonclosure are overall smaller at NF10 than at VFO, with an energy balance ratio (Wilson et al., 2002)

$$E BR = \frac{\sum (LE^* + H^*)}{\sum (R_{net}^* - G^*)}$$

of 0.54 and 0.76, respectively. At NF27, on the other hand, the very small daytime radiation values during the few days with all data lead to an EBR of 0.71 and a negative residual in the afternoon. At VFO and NF10, the residual becomes only negative around sunset, which, however, stays at relatively large negative values throughout the night as a result of small heat fluxes compared with the negative net radiation. Similar results were observed by Rotach et al. (2008) on the valley floor of the Swiss Riviera Valley, where the magnitude of the sum of sensible, latent, and ground heat flux was distinctly smaller than the negative net radiation after sunset. Stoy et al. (2013) showed an increase of the instantaneous EBR, that is, individual half-hour values, with increasing friction velocity. Data from VFO and NF27 show a similar trend, also for normalized friction velocity $u^*_f$ (not shown). One explanation for the frequently observed nonclosure of the surface energy balance are large eddies or advection from quasi-stationary circulations due to surface heterogeneities (Foken, 2008; Mauder et al., 2010). Because of the observed pronounced valley- and slope-wind circulation in the Inn Valley during the analyzed VWDs, nonclosure of surface energy balance is thus not unexpected and consistent with the above theory. Massey et al. (2017), for example, correct the sensible and latent heat fluxes for the effect of large eddies by distributing the residual between them according to the Bowen ratio, assuming that $\beta$ is the same across the whole spectrum.

The horizontal heat fluxes in Figure 8 are multiplied by $\rho c_p$ and normalized by the maximum solar radiation at the top of the atmosphere at VFO so that they are directly comparable to the vertical heat fluxes. The longitudinal (ground-parallel) heat flux $\rho c_p u T'$ follows a similar diurnal cycle as the vertical heat flux. The morning transition from positive to negative fluxes coincides approximately with the transition from negative to positive values in $H^*$ and vice versa in the evening. The longitudinal heat flux thus opposes the valley wind during daytime, which flows parallel to the along-valley temperature gradient. In the afternoon, $\rho c_p u T'$ changes sign when cooling starts in the valley and the along-valley pressure gradient begins to weaken (see Lehner et al., 2019). At VFO and at the south-facing sites, daytime values have a similar magnitude as $H^*$ and nighttime magnitudes of the longitudinal heat flux are similar to the daytime and thus significantly larger than $H^*$. At the north-facing sites, which are less influenced by the along-valley wind, $\rho c_p u T'$ remains, however, mostly negative throughout the night and does not show a perceptible diurnal cycle, with much lower values than at the other valley sites before noon. Only during the summer and spring months, the flux reverses to positive values in mid to late afternoon together with the other sites, but only for a short period, returning to negative values already around sunset (Figure S2j). The
diurnal cycle at MT21 differs strongly from the valley sites, with a pronounced positive maximum in the afternoon. The interquartile range is, however, large because of a single summer day that has a strong negative afternoon peak instead of the wintertime positive maximum. The lateral heat flux $\rho c_p v^T$ is about an order of magnitude smaller than the longitudinal and vertical fluxes, without a pronounced diurnal cycle. NF27 and SF8 differ in that they have weak but distinct positive and negative values, respectively, starting in mid-afternoon.

### 3.4 Momentum fluxes

Median diurnal cycles of turbulent kinetic energy (TKE) closely follow the diurnal cycles of wind speed (Figures 6a and 10a), resulting in an increase in the morning, which is somewhat delayed compared with the increase in wind speed and $H^*$. A distinct maximum occurs in the afternoon at all sites except for SF1, approximately simultaneously with the peak in wind speed. Similar to wind speed, the north-facing sites have overall the lowest TKE. The highest TKE values in the morning are found at SF1 as a result of the increased wind speed at the time of sunrise (Figure 6a). It then reaches a maximum already around noon, except for in the summer months when the maximum is equally shifted to the afternoon (Figure S2k). In the afternoon, TKE is highest at MT21, with values about twice as high as in the valley. Within the valley, the highest afternoon values occur at SF8 where, in particular during the summer months, values similar to MT21 can be reached (Figure S2k), consistent with high values in sensible heat flux (Figure 8). Individual days may also show a distinct morning maximum, although weaker than
the afternoon maximum. The magnitude of the morning values varies little throughout the seasons, while the magnitude of the afternoon maximum undergoes a seasonal cycle similar to wind speed, even when normalized, with highest values in spring and summer and values similar to the morning in the fall. TKE decays again after sunset, together with the weakening in wind speed and $H^*$. Horizontal contributions to TKE are much larger than vertical contributions, with $u'^2$ and $v'^2$ being a factor of about 2–3 larger than $w'^2$, as can be seen in the velocity aspect ratio $VAR = \left( \frac{2w'^2}{u'^2 + v'^2} \right)^{1/2}$ (Vickers and Mahrt, 2006), with the lowest values at VF0 and the highest at SF8 and MT21 (Figure 10b). The diurnal cycles of the velocity variances, however, are generally very similar to the diurnal cycle of TKE. $VAR$ increases at all sites after sunrise or in the early morning, remaining almost constant throughout the day until after sunset, when it decreases again slowly. Only at NF10, the decrease to nighttime values happens already around noon. The nighttime values at VF0 are much lower than at the other sites, which may be a result of the strong valley inversion and thus high nighttime stability at VF0 and SF8, resulting in particularly low vertical velocity variances compared with the horizontal variances.

The friction velocity $u^*_f$ has a very similar diurnal cycle as TKE, with a first increase in the morning after sunrise and a second increase around noon, but with weak morning values at the north-facing sites, which continue until the afternoon at NF10 (Figure 10c). The magnitudes at the different sites relative to each other are also similar to those of TKE, with the exception of a more pronounced morning maximum at VF0. In contrast to SF8, wind speed increases more rapidly with height at VF0 (Figure 6a), thus increasing vertical wind shear and $u^*_f$.

The longitudinal (ground-parallel) momentum flux $\overline{u'w^*}$ is generally negative or close to zero at all sites (Figure 10d), except for NF27 during the morning hours. This could indicate the presence of shallow katabatic flows at NF27, with a wind speed maximum below the measurement height at 6.8 m AGL. The magnitude of the lateral momentum flux $\overline{v'w^*}$ is mostly smaller than $\overline{u'w^*}$, except for MT21, where the two fluxes are of similar magnitude (Figure 10e). The high values in $\overline{v'w^*}$ at MT21 in the middle of the afternoon coincide approximately with high values in wind speed, but occur slightly earlier. Large negative values of $\overline{v'w^*}$ are also found at NF27 in the afternoon. The near-surface wind direction at NF27 deviates somewhat from the up-valley direction dominating at the other sites (Figure 6b). The large values of $\overline{v'w^*}$ could thus be a result of vertical wind shear, as the flow rotates more into the up-valley direction away from the slope. Similarly, large values of $\overline{v'w^*}$ are found at SF1, positive in the morning and negative in the afternoon.

4 | VERTICAL VARIATIONS IN THE DIURNAL CYCLES OF TURBULENT FLUXES

In the surface layer, the turbulent fluxes are by definition approximately constant with height. In reality, particularly over complex, inhomogeneous terrain, this is not necessarily true (Sfyri et al., 2018). Looking at all the data from VF0 between summer 2013 and the end of 2015 that satisfy certain quality criteria, Sfyri et al. (2018) determined that the heat flux is constant with height only about half of the time and the momentum flux even only during 1% of all time periods, requiring both $\overline{u'w^*}$ and $\overline{v'w^*}$ to be constant with height. To determine the frequency of constant fluxes with height similar to Sfyri et al. (2018), but during VWDs, we define a constant flux if either the respective flux is very small at all measurement heights (i.e., $wT_q < 0.01$ K-m-s⁻¹, $\overline{u'w^*}$ and $\overline{v'w^*} < 0.01$ m²-s⁻², and $\overline{w^2q^*} < 10^{-5}$ kg-m²-s⁻¹) or if the change in flux between individual levels is less than 20% of the surface value. To compare with Sfyri et al. (2018), a constant heat flux thus results in about 62% of the periods at VF0, a constant moisture flux in about 72% of the periods, and a constant momentum flux in about 28% of all periods, considering all the data and not only VWDs. Sfyri et al. (2018) used a slightly less restrictive definition of constant fluxes with height, requiring the fluxes not to change by more than 20% between adjacent levels. On the other hand, they used more restrictive quality criteria, specifically, the high-quality criteria defined by Stiperski and Rotach (2016). The high-quality criteria used by Sfyri et al. (2018), excluding non-stationary data, strongly reduces the number of periods with small values below the above thresholds. On the other hand, their stricter definition of constant fluxes reduces the number of constant-flux periods at VF0.

Median diurnal cycles of $H^*$ are almost identical at different levels for VF0 and NF27 during VWDs (Figure 11), thus suggesting near-constant fluxes with height, whereas at SF8, $H^*$ is overall much larger at the lower measurement level, particularly during the morning. This pattern is most pronounced between fall and spring (not shown). Comparing the morning footprint areas in Figure 2b between the two vertical levels shows that, while the smaller footprint for the lower sensor includes mainly grassland and some concrete surface, the larger footprint for the upper sensor includes different types of vegetation. At NF27, on the other hand, the vegetation type does not vary considerably in either footprint. To further explore this, the number
of 30-min periods with constant heat flux was calculated based on the above definition, only for unstable periods during VWDs. Unstable periods were selected to represent daytime conditions when fluxes are comparatively large and their vertical variations can be seen clearly in Figure 11. Focusing on daytime VWD conditions leads indeed to a drop in the number of constant-flux periods, particularly at SF8 from about 52% for all unstable periods to about 30% during VWDs. At VF0 and NF27, the drop is slightly less pronounced from 58 to 47% and from 56 to 45%, respectively.

The sensible heat flux generally reverses sign already in the middle of the afternoon, reaching a minimum value before sunset. Temperature measurements at multiple vertical levels are available for VF0 for the period July 2018 to December 2019. Median diurnal cycles of the vertical potential-temperature gradients calculated between the individual measurement levels are shown in Figure 12 together with the median sensible heat flux for four VWDs when complete diurnal cycles of $H^*$ and temperature at all levels are available. The median diurnal cycle of $H^*$ for these four VWDs is similar to that of the entire analysis period (Figure 11b) in that the heat flux changes sign between noon and mid-afternoon at each of the three levels. Potential temperature was calculated with respect to the ground, that is, $\theta = T + g/c_p z$, where $T$ is the measured temperature, $g$ the acceleration due to gravity, $c_p$ the specific heat at constant pressure, and $z$ the height above ground. The potential-temperature gradient between 4 and 8.7 m AGL also changes sign around solar noon to become stable. The layer closest to the surface (2–4 m AGL) remains, however, unstable so that a shallow stable layer is embedded between the super-adiabatic near-surface layer and the near-neutral layer above.

Vertical variations of the latent heat flux can only be analyzed at VF0, as the other sites are only equipped with a
Figure 12 Median diurnal cycles of (a) normalized sensible heat flux at levels L1–L3 and (b) vertical potential-temperature gradient between different measurement heights of VF0 for four VWDs in August 2018 (August 18–21), when simultaneous sensible heat flux measurements and temperature measurements at all vertical levels were available. Additional diurnal cycles of radiation, wind, and near-surface turbulent fluxes for the four VWDs are shown in Figure S4 in the online supporting information, Appendix S1.

single fast-response hygrometer (Figure 11). At VF0, however, the diurnal cycles suggest a decrease of LE* with height during VWDs. While this result can also be found during the summer months, but not during the fewer spring days, it may be somewhat biased by a relatively large number of fall and winter cases (eight) going into the average at the lowest level, whereas only one winter day is available from the top measurement level. Differences may also be related to a larger variety of vegetation types in the larger footprint area for the upper sensor (Figure 2). The number of periods with constant fluxes for unstable VWD conditions is, however, approximately the same as for all unstable periods between 2014 and 2019, with approximately 65% and 66%, respectively.

The number of periods with constant momentum fluxes $u'w'$ and $v'w'$ is also almost identical during unstable VWD periods compared with all unstable periods at VF0, with 21% of the data points. At SF8 and NF27, on the other hand, a small difference occurs from about 19 to 15% and from 10 to 8%, respectively. Figure 11 shows a weak minimum in the magnitude of the vertical transport of longitudinal momentum at level 2 at VF0 and near-constant median $u'w'$ during the afternoon at SF8, with a weak decrease in magnitude with height in the morning. At NF27, $u'w'$ changes sign with height in the morning, from weakly negative near the surface to weakly positive higher above, suggesting the presence of a katabatic flow with a jet maximum between the two measurement levels. In the afternoon, the magnitude of the momentum flux increases with height. The vertical flux of lateral momentum is generally small at all three levels of VF0 and at the uppermost level at SF8. Values at the lower level and at NF27 are, however, much larger in magnitude, thus resulting in a relatively strong decrease with height at SF8, particularly in the afternoon. TKE is near constant with height in the morning at all three sites, with an increase with height at SF8 and NF27 in the afternoon and a short period with decreasing TKE with height at VF0 in the second half of the afternoon, even though median wind speeds also increase with height during this time period.

5 Discussion

Previous observations of diurnal cycles of turbulent fluxes in north–south-oriented valleys, for example, the Brush Creek Valley in Colorado (Whiteman et al., 1989b) and the Riviera Valley in Switzerland (Rotach et al., 2008), have revealed a large impact of slope orientation and thus of solar irradiation on the timing of turbulent heat fluxes and their peak values. With the diurnal cycle of the sensible and latent heat fluxes closely following the diurnal cycle of solar radiation, the maximum values were observed in the morning and in the afternoon on east-facing and west-facing slopes, respectively. Observations presented here from the approximately east–west-oriented Inn Valley, on the other hand, show that there is little difference in the timing of the heat fluxes between the north- and south-facing sidewalls. Instead, the sensible heat flux peaks on average before or around solar noon at all sites, while the latent heat flux reaches its maximum generally in the early afternoon. Other processes, such as local surface characteristics and the thermally driven slope- and valley-wind circulation, thus seem to be dominant factors modifying turbulent exchange to result in a deviation of the diurnal cycles from symmetry about solar noon. Shading and differences in the magnitudes of solar radiation between north- and south-facing slopes, however, affect the strength of turbulent fluxes.
A characteristic of the turbulent fluxes in the Inn Valley is the early “evening” reversal of the sensible heat flux, which occurs on average in the middle of the afternoon, that is, oftentimes several hours before local sunset. At the valley floor site, the reversal can even occur at local noon on individual days (e.g., the days in Figure 12). An example of the energy balance on a single day at a site near Innsbruck shown by Vergeiner and Dreiseitl (1987) also showed this early reversal, which was, however, relatively weak and short. Blay-Carreras et al. (2014) define the start of the afternoon transition as the peak and subsequent decrease in the sensible heat flux. According to this definition, the afternoon transition could thus start at or before solar noon in the Inn Valley. After the reversal, negative heat fluxes in the afternoon can reach magnitudes similar to the positive morning maxima. The exception is site SF8 on the south-facing sidewall, which is located close to a concrete surface and a gravel pit and typically experiences higher sensible heat fluxes and Bowen ratios than the other sites. At this location, the flux reversal occurs only in the second half of the afternoon. Corresponding temperature measurements at the valley floor site indicate that the vertical temperature gradient between 4 and 9 m AGL reverses sign at the same time to become stable, while the near-surface layer remains unstable. The observations are thus not consistent with the oasis effect (Oke, 2000) in that the surface and near-surface air actually remain warmer than the air farther aloft, which also suggests that the sensible heat flux below the lowest measurement level at 4 m AGL remains positive. Heat flux minima after the flux reversal have also been observed at other complex-terrain sites, particularly at sites where the flux changes sign relatively early compared with sunset (Whiteman et al., 1989b; Rotach et al., 2008). These minima had, however, generally lower magnitudes compared with the daytime maxima. Other studies in complex terrain, on the other hand, show flux reversals that occur after sunset, with values close to zero immediately after the reversal (Martinez et al., 2013; Jensen et al., 2016). This suggests that the magnitude of the negative heat fluxes is related to the time of flux reversal and that large negative values occur only before sunset when turbulence is generally strong. The flux reversal in the Inn Valley seems to be closely related to the valley wind circulation, as the peak in the sensible heat flux is oftentimes reached at the time of the transition from down-valley to up-valley winds at local noon, that is, the heat flux starts to decrease with the onset of the up-valley wind. Example case studies in Figure S4 in the online supporting information, Appendix S1 show this correlation in the peak of $H$ and the time of the flow transition at VF0 and NF10. A detailed analysis of this phenomenon is the topic of a future study.

Over flat and horizontally homogeneous terrain, the horizontal turbulent heat flux divergence is typically small compared with the nonturbulent flux divergence, in contrast to the vertical turbulent flux divergence. In the complex, mountainous terrain of the Inn Valley $u′T'$ varies, however, considerably from site to site. It reaches magnitudes similar to $w′T'$ during daytime and can even exceed it during nighttime. Similar ratios of $u′T'$ and $w′T'$ have been observed for flat-terrain (Wyngaard et al., 1971) and sloping (Oldroyd et al., 2016) sites. Oldroyd et al. (2016) have also shown that horizontal heat fluxes play an important role in the buoyancy production of turbulent kinetic energy. Similarly, the vertical turbulent flux of lateral momentum is usually small over noncomplex terrain and is thus oftentimes neglected in the calculation of the friction velocity (Rotach et al., 2008). Previous studies have already shown for a slope in the Swiss Riviera Valley (Van Gorsel et al., 2003; Rotach et al., 2008) and the Owens Valley, California (Babić et al., 2017), that $v′w′$ is not negligible and thus contributes to the total shear stress. The large vertical flux of lateral momentum compared with flat terrain results from directional wind shear with height, as shallow slope winds occur immediately above valley sidewalls, with along-valley winds farther away from the slope. Similarly, large values of $v′w′$ were also found at some of the i-Box sites, including a steep valley sidewall, where the near-surface wind direction in the afternoon deviates from the up-valley wind observed at other sites. Wind shear associated with thermally driven circulations in the Inn Valley also impacts the calculation of TKE in planetary boundary layer (PBL) parameterizations in numerical models, resulting in a nonnegligible contribution from horizontal shear production (Goger et al., 2018; 2019).

Median diurnal cycles draw a consistent picture in that spatial variations in heat and momentum fluxes occur as a result of variations in solar radiation, local terrain and surface characteristics, and valley wind circulation. In addition, however, day-to-day variations occur in the diurnal cycles of turbulent fluxes. Despite similarities in radiation and valley wind conditions during consecutive VWDs, distinct differences can occur in turbulence intensity and turbulent fluxes. Considering the restrictive selection of VWDs (Lehner et al., 2019), only a very small number of periods with multiple consecutive or near-consecutive VWDs exists. One such period occurred between August 16 and 21, 2018, which is shown in Figure S4 in the supporting information. In particular, pronounced differences can occur in the timing and magnitude of the peak in sensible heat flux. While it peaks on average before solar noon and its timing is related to the valley wind reversal, it may continue to increase past the noon valley wind transition.
on individual days to reach much higher magnitudes. This occurs particularly frequently at SF8.

The number of VWDs is relatively small in the present study, with 74 days during a period of 6 years. This is a result of the fairly strict VWD identification criteria defined in Lehner et al. (2019). Tests with a less stringent VWD definition, which included a slightly relaxed geopotential-height gradient threshold and allowing a larger fraction of cloudy conditions per day (i.e., up to 40% cloudy conditions instead of up to 10%), resulted in a total of 177 VWDs, but almost no differences in the diurnal cycles presented in this study and only small changes in the variability (Figure S5 in the online supporting information, Appendix S1). The results are thus also applicable to less ideal conditions.

The relatively low number of VWDs in combination with an uneven distribution of these VWDs throughout the year (Table 2) also means that not all seasons are equally represented in the discussed median diurnal cycles. Particularly the number of winter and spring days is comparatively small. The diurnal cycles of the turbulent fluxes, however, have a seasonal cycle (Figure S2) because of the change in available energy from solar radiation throughout the year. While many features discussed in this paper are applicable to all seasons, it has to be kept in mind that seasonal differences exist and that some of the median curves shown in the manuscript may not be equally representative of each season. For some of the variables, no data exist during individual months. For example, for the latent heat flux at VF0 and SF1, no data are available for VWDs in fall and winter, respectively (Figure S2). These seasons are thus not represented in the median diurnal cycles over the whole dataset. Other variables have a particularly strong seasonal cycle and thus a large variability when analyzing the whole year, for example, shortwave radiation components at NF10 because of variations in local sunrise at the site (Figure S2).

In winter and spring, relatively strong day-to-day variations can occur in the local surface properties as a result of temporal snow cover. As snow cover can only be identified on the basis of radiation measurements with the present dataset and thus only for a subset of the stations, days with snow cover were not removed from the analysis. However, to test their impact on the overall results, VWDs with snow cover were identified for VF0, NF10, NF27, and MT21, yielding only a total of 3, 5, 1, and 7 days, respectively. Their influence on the diurnal cycles was relatively small, with the exception of the momentum fluxes and the horizontal heat flux at MT21, where the fraction of days with snow cover is comparatively large because of the generally lower number of VWDs with good data availability (Figure S6 in the online supporting information, Appendix S1).

6 SUMMARY

Observations from the six i-Box eddy-covariance stations (Rotach et al., 2017) in the approximately southwest-northeast-oriented Inn Valley, Austria, were used to determine median diurnal cycles of radiation, wind, and near-surface turbulent fluxes during synoptically undisturbed, clear-sky conditions (valley-wind days, VWDs). Because of restrictive VWD selection criteria (Lehner et al., 2019), only a small number of 74 days qualified as ideal undisturbed, clear-sky days during the 6-year long analysis period. The measurement sites are located within an approximately 6.5-km long section of the valley, with a cross-valley distance of about 3 km. Considering the grid spacing of current operational global weather prediction models, for example, of the European Centre for Medium-Range Weather Forecasts (ECMWF) Integrated Forecast System (IFS) model with 9.6 km, all of the six sites could be located within a single grid cell. The respective terrain and surface characteristics differ, however, significantly, ranging from agricultural fields on the valley floor to grassland on the north-facing sidewall, agricultural fields and a concrete surface on the south-facing sidewall, and a mountain top. This diversity in slope orientation and land cover is reflected in a large variability of the fluxes among the sites, which is further related to the valley- and slope-wind circulation that determines the wind field in the valley during VWDs.

The key characteristics of the valley wind circulation and near-surface turbulent fluxes can be summarized as follows:

• Magnitudes in incoming solar and net radiation are small on the north-facing valley sidewall compared with the valley floor and unobstructed mountain-top sites, strongly reducing the available energy. The timing in the maximum of solar irradiation differs, however, relatively little among the sites compared with differences between east- and west-facing sites observed in previous studies (Figure 4), in agreement with theoretical calculations (e.g., Whiteman, 2000).

• Large spatial variations occur in the dominant wind regimes. While the valley wind circulation dominates the observed near-surface wind at the valley floor and at the south-facing sidewall sites, the near-surface wind is more strongly influenced by local slope winds on the north-facing sidewall sites (Figure 6).

• The valley wind circulation is determined by a south-westerly down-valley wind at night and during the morning. The flow transitions to up-valley around solar noon and back to down-valley after sunset. The near-surface valley wind has two pronounced daily wind speed maxima, the first during the
down-valley-wind period in the morning and the second during the up-valley-wind period in the afternoon (Figure 6).

- Large spatial variations occur in the turbulent sensible and latent heat fluxes as a result of (a) variations in available energy, with lower heat fluxes on the steep north-facing sidewall site, particularly between fall and spring, and (b) variations in energy partitioning, with a high sensible heat flux near a large concrete area and large latent heat fluxes over agricultural land during spring and summer (Figures 8 and S2).

- Similarly large spatial variations occur in turbulence kinetic energy and turbulent momentum fluxes (Figure 10).

- While the median latent heat flux reaches its peak in the early afternoon, the median sensible heat flux peaks before solar noon and changes its sign already around mid-afternoon. Negative values after the flux reversal can reach magnitudes similar to the positive morning values (Figure 8).

- The residual of the surface energy balance is of a similar magnitude as the turbulent fluxes. As net radiation is largely balanced by the latent heat flux, which reaches its peak in the afternoon, the nonclosure of the energy balance decreases during the daytime. It reaches, however, very large values during the morning and evening transition periods.

- The mountain-top site differs from the valley sites, with a pronounced peak in the median horizontal and sensible heat fluxes occurring in the afternoon that is about three times larger than at the valley sites (Figure 8).

- Horizontal turbulent heat fluxes and vertical fluxes of lateral momentum \( (\nu'w') \) can reach magnitudes similar to the vertical heat flux and the vertical flux of longitudinal momentum \( (u'w') \), respectively (Figure 8).

- Turbulent fluxes are not necessarily constant with height during VWDs (Figure 11). Depending on the site, a constant sensible heat flux is observed in about 30–40% of all cases and constant momentum fluxes in about 10–30%.

The work presented here focuses on synoptically undisturbed, clear-sky conditions, during which solar radiation is the primary forcing mechanism and direct solar radiation is the largest contribution to total global radiation. As local terrain properties have the largest impact on direct radiation, spatial variations in irradiation and thus turbulent fluxes resulting from differences in slope angle and orientation can be expected to be smaller during strongly cloudy days, when direct radiation is damped. During synoptically disturbed conditions, when large-scale forcing mechanisms dominate, spatial variations due to local effects may also be expected to be smaller. During situations, however, when the terrain strongly influences flow conditions, such as during foehn events in the Inn Valley (e.g., Haid et al., 2020) or during frontal passages, small-scale variations in turbulence intensity are likely large.

ACKNOWLEDGEMENTS
We thank all the colleagues, students, and in particular the technicians at the Department of Atmospheric and Cryospheric Sciences at the University of Innsbruck whose ongoing contributions make it feasible to collect high-quality data as part of the i-Box project. The i-Box infrastructure was established through funding by the University of Innsbruck. We appreciate the constructive suggestions from two anonymous reviewers.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

**How to cite this article:** Lehner M., Rotach MW, Sfyri E., Obleitner F. Spatial and temporal variations in near-surface energy fluxes in an Alpine valley under synoptically undisturbed and clear-sky conditions. *Q.J.R. Meteorol. Soc.* 2021;147:2173–2196. https://doi.org/10.1002/qj.4016.