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Oscillating nocturnal slope flow in a coastal valley

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ABSTRACT

Observations of slope flows in a coastal valley are analyzed. The diurnal variation of upslope and downslope flows depends on season in a systematic way which appears to be related to the high latitude of the observational site and the presence of a nearby layer of marine air. Summer nocturnal flow over the sloping valley floor was studied during a special observing campaign. A downslope gravity flow interacts with even colder surface air at the valley floor. The latter originates as cold marine air or previous drainage of cold air. Regular oscillations, which appear to be trapped, terrain-related, internal gravity waves, exert a major influence on the downslope flow and its interaction with pre-existing cold air at the floor of the valley.

1. Introduction

The diurnal variation of surface heating and cooling generates circulations up and down the sloping floors of valleys as well as up and down the sidewalls. The valley floor circulation is generally found to lag the flow down the sidewalls of the valley (Geiger, 1975; Banta, 1984). With the onset of surface radiational cooling in the evening, cold air drains down the sides of the valleys which eventually leads to a flow of cold air down the valley floor towards the valley outlet. The drainage of cold air down the sides of the valley is thought to maintain flow of cold air down the valley floor throughout the night.

However, air which is draining down the sides of the valley may become warmer than the air which has collected in the valley (Heywood, 1933) due to entrainment warming of the air descending the sides of the valley and due to continued radiational cooling of slowly moving surface air at the valley floor. In fact, a thermal belt is often observed along the slope above the valley (e.g. Geiger, 1975; Schnelle, 1963). Similarly, dense oceanic gravity currents descending coastal slopes are observed to warm through entrainment and then flow horizontally at a level of buoyancy equilibrium well above the ocean floor (Turner, 1981).

The present study examines the interaction of cold air which has collected in a valley, with drainage of cold air from further up the valley. Observations are collected during 6 summer nights in and above the Dyrnæs valley on the West Coast of Greenland. Since the nearby ocean temperatures are comparable or colder than the nocturnal minimum temperatures over land on most of the nights, marine air penetration could have contributed to the cold temperatures in the valley. The flow is significantly modulated by regular oscillations with periods predicted by simple theory of internal gravity waves. Features of this flow situation are expected to be widespread since internal gravity waves are obligatory in stratified airflow near the surface and slope flows are frequently observed to be warmer than the air at the valley floor.

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2. Site description

The Dyrnæs valley is situated in the south-western part of Greenland at latitude 61° N and longitude 46° W. The valley is situated on a peninsula that extends south-west to north-east. During summer, the icebergs drifting along the coast of Greenland keep the surface temperature of the open sea around 2 °C; the water surface temperature in the fjords increases inland and is typically 5–7 °C in the sound outside the Dyrnæs valley, (DHI, 1979).

Fig. 1 shows a detailed map of the Dyrnæs valley. The valley surface is irregular. The vegetation consists mainly of grass and creeping bushes. Large areas are without vegetation.

3. Meteorological measurements

To provide information about the local climate in and around the Dyrnæs valley, automated meteorological measurements were carried out in the area from September 1979 to March 1983 (Kristensen, 1983). More detailed measurements of the nocturnal flow field were carried out during a two-week special observing campaign in the summer of 1981 (Gryning and Lyck, 1983).

3.1. Automated measurements

Standard meteorological measurements were carried out at two 21 m high masts over a 3-year period. One mast was situated at a plateau close to the 300 m descent to the valley (K, Fig. 1). The other mast (V, Fig. 1) was situated in the middle of the Dyrnæs valley about 800 m south-east of the plateau mast. The two masts are identically instrumented with wind speed measured at 5, 10 and 21 m heights, wind direction at 10 and 21 m, temperature at 2 and 20 m and temperature difference between 2 and 20 m. A Stevenson screen for temperature, humidity and pressure measurements is mounted at the 2 m level. Measurements of the wind speed are carried out with a Risø model 70 cup-anemometer, wind direction is sensed by oil damped wind vanes, and temperature is measured by means of platinum wire thermometers in radiation screens. All measurements are taken every 10 min. Wind direction, temperature and temperature difference are instantaneous values. The wind speed is averaged over a period of 10 min.

3.2. Special measurements

In 1981, more detailed measurements were implemented during 6 summer nights. These

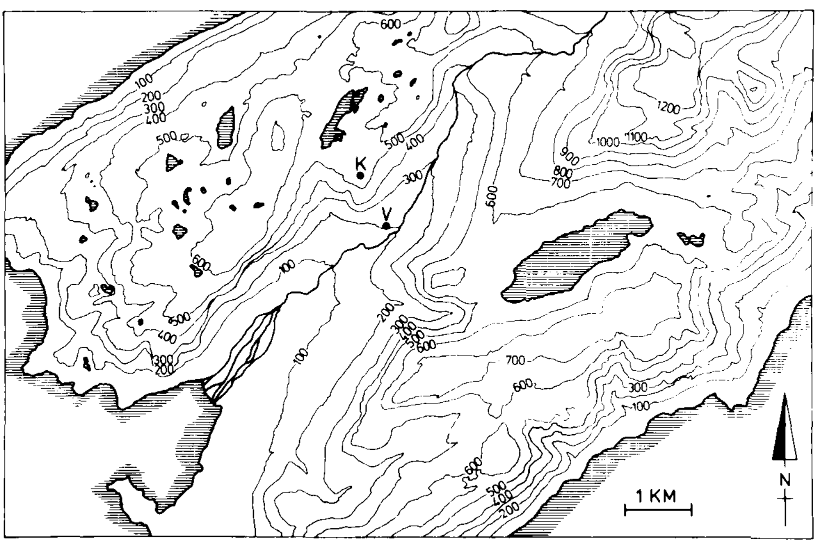

Fig. 1. Orographic map of the Dyrnæs valley. The position of the meteorological mast at the plateau is indicated by K, and the mast in the valley by V. Heights are shown in meters above mean sea level.

included mean and fluctuating wind velocity and fluctuating temperature at 23 m on the valley mast. The instrumentation is described in detail in Gryning and Thomson (1979) and Gryning (1981). A light-weight cup-anemometer (Risø model 70) is used to measure wind speed fluctuations. The distance constant is 1.5 m and the starting speed is 0.26 ms^{-1}. Wind direction is sensed using a light-weight vane with a natural wavelength of 1.5 m and a damping ratio of 0.5. Vertical wind velocities are sensed with a vertically mounted propeller. However, the vertical velocities were so small that the propeller was inappropriate for measuring these fluctuations. Temperature fluctuations are derived from the instantaneous temperature difference between a thermocouple junction extending 5 mm into the air stream and a reference junction embedded in the centre of a 10 cm acrylic sphere. The signals from the instruments were recorded continuously during the experiments and were later digitized with a frequency of 1 Hz.

During the observation periods, mini-radiosondes were launched at the valley mast. The sondes measured pressure, air temperature and wet bulb temperature. They were flown with an ascent velocity of about 1.5 ms^{-1}. Data were transmitted from the sonde every 3 s.

4. Climatological behaviour

The direction of surface airflow in the Dyrnæs valley is strongly influenced by season and diurnal modulation. In winter, the air motion is down the valley most of the time (Fig. 2), reflecting general drainage of very cold air from the Greenland interior accompanied by little diurnal variation of temperature (Fig. 3).

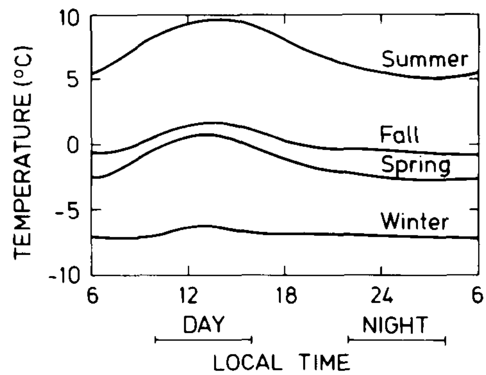

Fig. 3. Seasonal and diurnal variation of the mean temperature at the valley mast. See Fig. 2 for further explanation.

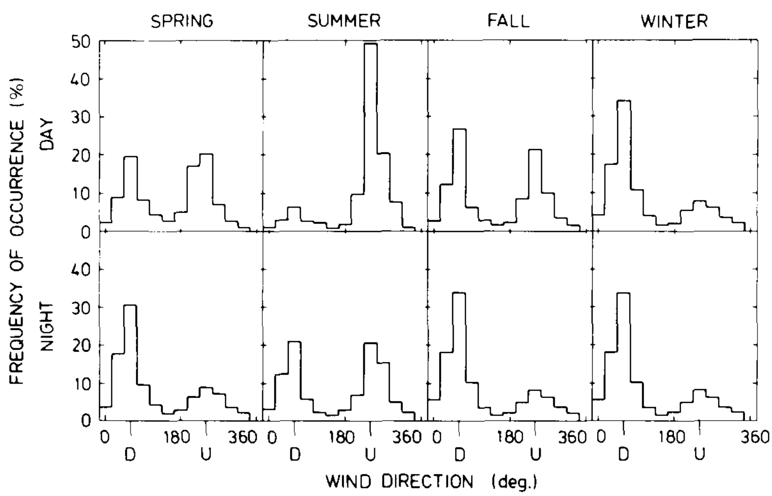

Fig. 2. Seasonal and diurnal frequency distribution of the wind direction at the valley mast derived from the consecutive 10 min samples. The four seasons are: Spring—March, April, May; Summer—June, July, August; Fall—September, October, November; and Winter—December, January, February. Day corresponds to the period 10–16; night to 22–04 local time. Down-valley flow direction is indicated by D, up-valley flow direction by U.

In the spring and fall, the surface air generally flows down the valley at night, but during the day, flows up or down the valley for roughly equal portions of time. A similar switching of wind direction occurs in the valley during summer nights. During the summer daytime, air generally flows up the valley in response to surface heating. Additional detail can be found in the study of Kristensen (1983).

Closer inspection of tower records indicates that the valley flow oscillation often takes place with a typical period of the order of 1 hour. Similar variations are not observed at the mast on the plateau.

5. Summer nocturnal valley circulations

The valley flow oscillation was observed during 5 of 6 nocturnal observing periods conducted during the 2-week field program (Table 1). The night with no wind oscillation during the observing period was characterized by cloudy skies and ambient flow in excess of 6 ms^{-1}. On 4 of the nights with flow oscillations, skies were clear and valley temperatures ranged between 3 and 7 °C. Such temperatures are believed to be characteristic of temperatures in the

Table 1. *Cloud cover and characteristic times for the meteorological measurements during the 1981 campaign*

Experiment	Measurements of fluctuating wind and temperature: start	stop	Time of radiosonde launches	Cloud cover
26 July	0:28	2:34	3:45*	clear
30 July	1:55	3:55	—	2/8
1 August	0:40	3:10	1:30	8/8
4 August	2:30	4:49	3:30	clear
7 August	1:52	3:45	2:50	clear
10 August	1:20	4:10	2:45 & 3:45	clear

* Released at the mouth of the valley.

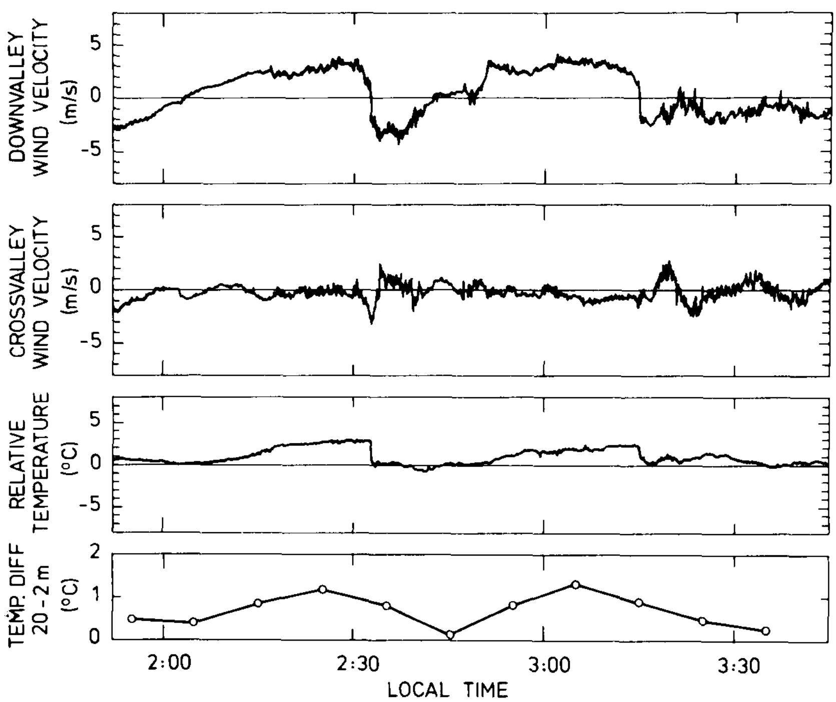

Fig. 4. Measurements at the valley mast of the fluctuating down-valley and cross-valley wind components and relative temperature for the experiment on 7 August 1981. The temperature differences are instantaneous values observed every 10 min.

outer part of the fjords away from the immediate shoreline. On the remaining night with valley flow oscillations, skies were cloudy and surface air temperatures in the valley remained near or above 10 °C.

The circulation oscillates between a flow of cold air directed up the valley and a flow of significantly warmer air down the valley with a period of 40–50 min. The depth of these circulations are not known exactly, although the radiosonde releases indicate a layer of especially cold and strongly stratified air in the lower 20–30 m with weaker, but still significant, stratification extending several hundred meters higher.

The flow directed down the valley is thinner than the flow up the valley. The level of the maximum averaged speed in the flow down the valley occurs between 5 and 10 m, while the maximum speed in the flow up the valley appears to occur near or above 10 m. For many of the individual cases, the speed of the up-valley flow was increasing between the 10 and 21 m observational levels and may have reached a maximum well above 21 m. Thus, the up-valley flow appears to occur over a layer much deeper than the mast, although flow in this direction was not observed at the plateau mast located about 300 m higher.

The flow directed up the valley passes the observational mast as a sharp front-like transition with rapid wind direction and temperature change, as is evident in the example shown in Fig. 4 and in the composite of all such transitions, Fig. 5. Then the flow up the valley usually decays gradually and eventually yields to weak down-valley flow. Flow down the valley slowly accelerates and warms until the up-valley flow once again advances as a sharp front. Sometimes, even colder air flows somewhat behind the passage of the front with the coldest air occurring when the up-valley flow has just vanished and is beginning to yield to down-valley flow, Fig. 5. This aspect of the flow is consistent with advection of air up and down the slope of the valley floor by an oscillating wind field.

Since the air flowing down the valley is a little warmer than the up-valley flow, it is more than simple return of the up-valley motion back down the slope as would occur with pure wave motion. Drainage currents from further up the valley or valley sides may contribute directly to the down-valley flow. Strong radiational cooling and cold air drainage does not seem to be a necessary condition

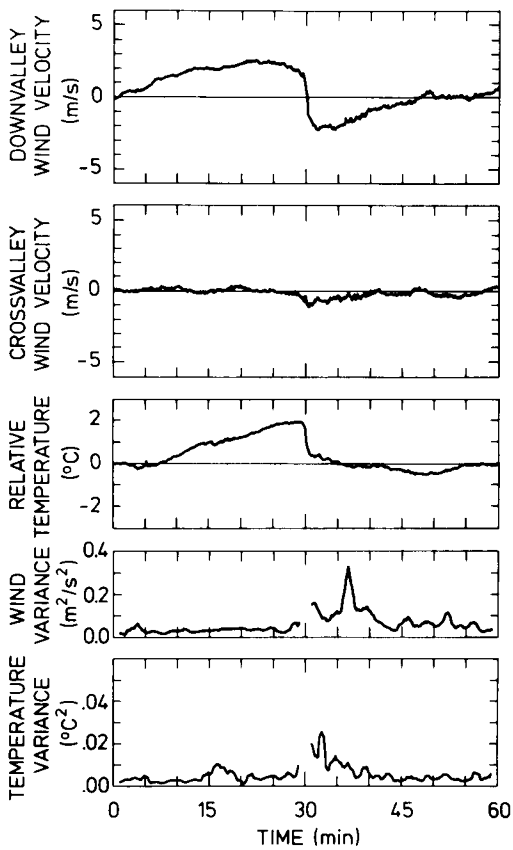

Fig. 5. Composite time history of the transition between down-valley and up-valley flow for the 7 cases that were documented in the 1981 campaign. The composite of a given variable is determined as the average over all of the cases for each point in time relative to the transition. The variance is constructed by computing the deviation from a 60 s running mean, squaring, re-applying the 60 s running mean and then averaging over all of the cases.

for the oscillation since it occurred, albeit with reduced amplitude, on one of the two experimental nights which were cloudy. Compared to the flow up the valley, the down-valley flow lasts about 30% longer (Table 2) and is characterized by a 25% stronger flow rate. Averaged over several oscillations, the net flow at the valley mast is directed down the valley. However, the net mass flux is not necessarily directed down the valley, since the weaker flow up the valley is deeper.

In the immediate vicinity of the front, the air moving down the valley first appears near the surface and then thickens. During the special

Table 2. *Averaged values of the 23 m wind speed U, the down-valley speed U_d, the up-valley speed U_u, the corresponding cross-valley flow V_d and V_u and the total time duration occupied by up-valley and down-valley flows t_d and t_u*

Experiment	U (ms^{-1})	U_d (ms^{-1})	U_u (ms^{-1})	V_d (ms^{-1})	V_u (ms^{-1})	t_d (min)	t_u (min)
26 July	0.5	1.5	−1.1	−0.1	−0.5	78	48
1 August	0.3	1.2	−0.8	0.2	−0.3	85	65
4 August	0.4	1.4	−1.5	0.1	−0.4	92	47
7 August	0.5	2.2	−1.6	−0.3	−0.2	62	51
10 August	0.0	1.1	−0.9	0.1	−0.3	77	91
average	0.3	1.5	−1.2	0.0	−0.3	79	60

observing period, 4 cases were captured where the flow at the 10 m level had just reversed to the down-valley direction while the flow at 21 m was still directed up the valley (as sketched in Fig. 6). In all 4 of these cases, the usual temperature stratification between the 2 and 20 m observational levels is eliminated. Turbulent mixing is implied and was independently verified by maximum activity of the vertical propeller. No cases were observed with up-valley flow at the 10 m level and down-valley flow at the 21 m level. The front moving up the valley is therefore sketched to be nearly vertical near the surface (Fig. 6).

The sharpness of the passage of the up-valley flow is probably related to terrain features. An internal gravity wave propagating from over the sea into the valley would encounter a significant steepening of the slope of the valley floor just prior to passing the observational site, Fig. 1. Sudden steepening has been observed to induce activity analogous to breaking of oceanic internal waves at a coastal slope (Stigebrandt, 1976; Perkin and Lewis, 1978). In addition, the flow encounters a relatively sharp constriction of the valley just upstream from the observational site. While the flow down the valley is accompanied by near zero cross-valley flow, the flow up the valley is observed with some cross-flow from northwest to southeast. Such cross-valley flow is consistent with the asymmetric narrowing of the valley in the proximity of the observational site.

Since the air descending the slope is not as cold as the air which ascends the slope, a net conversion of kinetic energy to potential energy appears to occur locally. The actual conversion rate cannot be evaluated, since the required perturbation quantities must be computed with respect to horizontal averages and not averages along the slope. The kinetic energy required to maintain such motions could be supplied by the pressure field of the internal wave motion which is examined in Section 6.

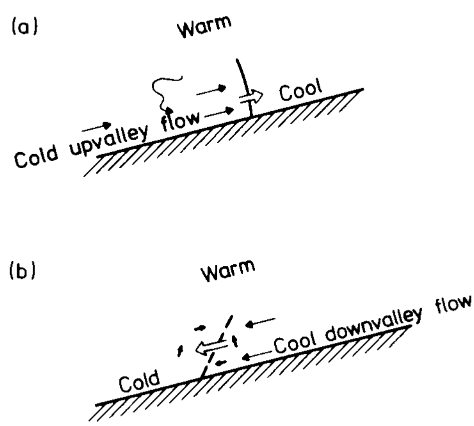

Fig. 6. Sketch of the flow transition regimes.

6. Internal gravity wave

The oscillation along the slope is consistent with rather simple internal gravity wave considerations. For example, proceeding with the usual linearization, neglecting variations of the mean flow and assuming incompressible flow, the resulting dispersion relationship (e.g. Haltiner, 1971, eq. 2.10) leads to the following expression for the wave period

$$T = \frac{2\pi}{N}[1 + (L/H)^2]^{1/2}, \tag{1}$$

where N is the Brunt-Väisälä frequency, L the horizontal length scale and H the height of the valley walls. Wave motions are assumed to be trapped below this height. If we imagine that the significant stratification is confined below the level of the average height of the ridges, then H is approximately 600 m above sea level. The radiosonde releases indicate generally stronger stratification below 600 m compared to that above this height, although a definite persistent top to the cold air could not be defined. The Brunt-Väisälä frequency for evaluation of eq. (1) is computed from the average stratification between 50 and 400 m above the valley mast (corresponding to 250 to 600 m above sea level) as observed from the radiosonde releases (Table 3).

Using eq. (1) and a typical terrain height of 600 m, internal gravity waves propagating between the land mass containing the Dyrnæs valley and the next land mass located about 5 km to the southwest are predicted to oscillate with a period of a little less than 1 h (Table 3). This value is comparable to the time period of the oscillations inferred from the individual records and from the maxima of composite spectra, Fig. 7.

Table 3. *Brunt-Väisälä frequency N and period for along-valley and cross-valley oscillations as calculated from eq. (1) (cal.) and as inferred from the maxima in the power spectra of the wind fluctuations measured at the mast (mea.)*

Experiment	N (10^{-2} s^{-1})	Along-valley period (min)		Cross-valley period (min)	
		mea.	cal.	mea.	cal.
26 July	1.7	55	51	18	19
1 August	1.8	39	49	21	19
4 August	2.1	55	41	25	16
7 August	1.8	39	49	12	18
10 August	1.8	55	48	14	18

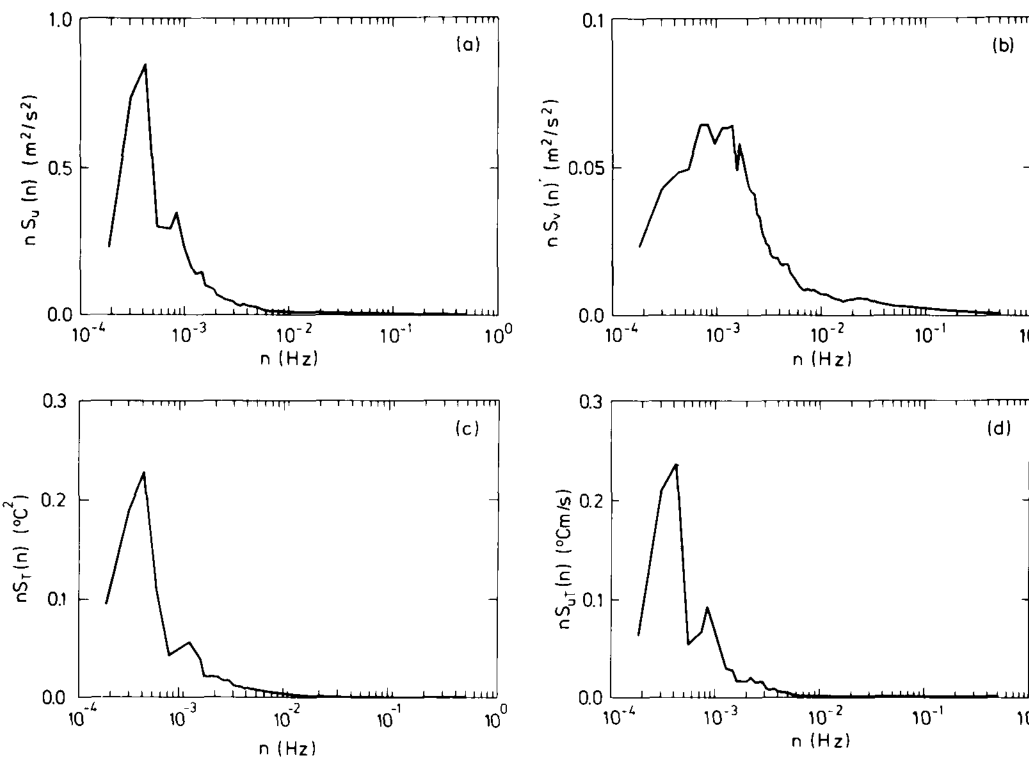

Fig. 7. Composite power spectra of (a) the along-valley velocity variance, (b) the cross-valley velocity variance, (c) the temperature variance and (d) covariance spectrum between the up-valley/down-valley flow and temperature.

The cross-valley flow also exhibits oscillations but with a shorter period of about 15 min, Fig. 7. Noting that the width of the valley is approximately 1200 m and the valley depth is approximately 400 m, and using the same Brunt-Väisälä frequency as before, eq. (1) indicates a period of roughly 15 min (Table 3) in agreement with the above observations. The interaction of the propagation of the front up the valley with the ridge extension northwest of the valley mast probably initiates cross-valley flow, which in turn could trigger the cross-valley circulations.

7. Conclusions

This study reveals some characteristics of flow of cold air down the valley side walls and down the weaker slope of the valley floor. The analysis concentrates on interaction between the downslope flow and pre-existing surface air in the lower part of the valley which is even colder.

The flow down the valley floor periodically yields to flow of colder air moving up the valley. The air moving up the valley passes the mast as a sharp front approximately every 45 min. This period is predicted by simple theory of internal gravity waves. During intervening periods, thin flow down the valley gradually re-establishes itself. The sharpness of the advance of cold air up the valley is probably associated with abrupt narrowing of the valley and steepening of the valley floor. Close to the front, significant mixing is observed between the air flowing down the valley and the cold pre-existing air occupying the lower part of the valley.

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