10.3 Intermittent turbulence and oscillations in the stable boundary layer: a system dynamics approach

Bas J.H. van de Wiel* , Arnold F. Moene, Oscar K. Hartogensis,
Reinder J. Ronda, Henk A.R. De Bruin, Albert A.M. Holtslag

Wageningen University, The Netherlands

1. INTRODUCTION

The stable boundary layer (SBL) is often characterised by turbulence which is not continuous in space and time. This so-called intermittent turbulence may affect the whole depth of the SBL. It is often reflected by oscilatory behaviour of the near surface temperature and wind speed. In the past this intermittency phenomenon has been studied mostly numerically (e.g. Revelle 1993, McNider 1995). In this study we use both a numerical as an analytical approach.

We focus on clear nights over land formed by cooling due to the strong surface radiation. In such cases often stability develops faster than shear, which causes the Richardson number to increase. As a consequence air becomes decoupled from the surface. Soon, however, air will be accelerated by the omnipresent pressure force until shear is strong enough to break down the stability causing a turbulence burst. Because of this strong mixing, shear is rapidly reduced and stability takes over. The situation has returned to its begin and the mechanism starts over again, causing intermittent bursts of turbulence and oscillations in the mean variables (Businger 1973).

Our goal is to describe and predict the above mentioned mechanism. We will use a simple physical SBL model, which is integrated numerically. Also, the model is studied analytically from a system dynamics point of view. This approach results in a dimensionless parameter, which is a function of external parameters controlling the system. With this parameter the equilibrium behaviour of the model (i.e. oscillatory or non-oscillatory) can be predicted.

2. MODEL DESCRIPTION

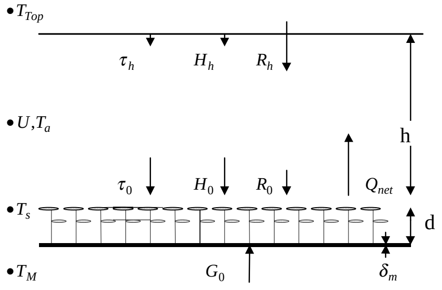

Figure 1: The model system: state variables, fluxes and model domain

Point of departure for the SBL model are the conservation equations for momentum and heat. Complexity of the model system is kept to a minimum, while preserving most important physical processes. By doing so the structure and dynamic interaction between the governing equations can be studied.

The conservation equations for momentum and heat for our system are given by:

$$\frac{\partial U}{\partial t} = -\frac{1}{\rho}\frac{\partial P}{\partial s} + \frac{1}{\rho}\frac{\partial \tau}{\partial z} \qquad (1)$$

$$\frac{\partial T_a}{\partial t} = \frac{1}{\rho c_p}\frac{\partial R}{\partial z} - \frac{\partial H}{\partial z} \qquad (2)$$

$$\frac{\partial T_s}{\partial t} = -\frac{1}{\rho_g c_g}\frac{\partial G}{\partial z} \qquad (3)$$

Some model characteristics/assumptions are:

1) Assumption of a fixed boundary layer height: no turbulent exchange with air above boundary layer.
2) No coriolis effects and no moisture effects.
3) First order turbulence closure, exchange coefficient depending on bulk Ri.
4) Emissivity approach for radiation.
5) Soil heat flux parameterized by vegetation resistence law (alternatively by a force-restore method for bare soil).

Due to this assumptions the generality of the present results may be limited. In future research the present framework will be extended to more general cases.

The equations are integrated over the domain of interest, which results in a system of three coupled non-linear differential equations describing the time evolution of the integrated values: U,Ta and Ts. This system is used in both the numerical and analytical analysis

3. MODEL RESULTS

The model presented in section 2 was integrated numerically. The time development of the surface temperature during a 10 hour transient run is shown in Fig. 2.

---

* *Corresponding author address:* Bas van de Wiel, Dept. of Meteor. and Air Qual. Duivendaal 2, 6701 AP, Wageningen, The Netherlands;
e-mail: Bas.vandeWiel@user.metair.wau.nl

A general decrease in surface temperature is seen, as is commonly observed in nocturnal conditions. After some time the temperature increases suddenly and drops back to the general trend after a short time. This result follows the results reported by Revelle (1993), who used a multi-layer model with comparable flux parametrisations for turbulence, soil heat flux and radiation, however incorporating Coriolis effects.

The time between the temperature peaks of about 1-2 hours is comparable with the time between temperature peaks reported by Revelle (i.e. 30-240 min.). The peak height of 4-5 K agrees with the peak height of the near surface temperature of about 5 K as in Revelle. Thus, the truncated model presented here essentially shows the same type of behaviour as the more complex model.

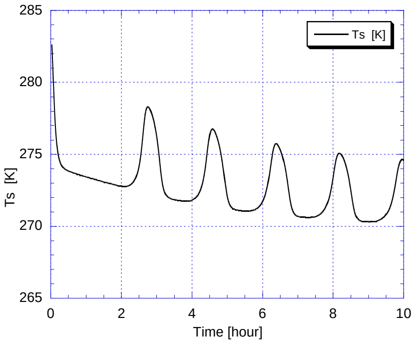

Figure 2: calculated time developement of surface temperature in a 10 hour transient run.

As an illustration in Fig. 3 also the intermittent behaviour of the turbulent fluxes is shown for the case given above (note that stationary solutions after 30 hrs. are shown).

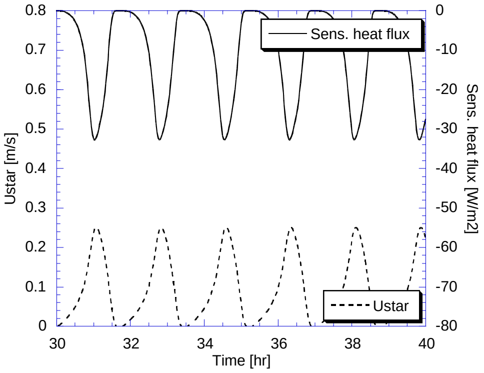

Figure 3: modelled fluxes in an equilibrium situation.

Furthermore, uppon a varying pressure gradient (keeping the other parametes at a constant value), in an equilibrium situation three regimes seems to exist in the present model:

a) The pressure gradient is weak. The equilibrium solution is non-oscillating, with weak turbulence resulting in a low surface temperature.
b) The pressure gradient is strong. The equilibrium solution is non-oscillating, with strong turbulence resulting in a relatively high surface temperature.
c) The pressure gradient is moderate. The equilibrium solution is oscillating, with intermittent turbulence and intermediate, but oscillating surface temperatures.

Of course, for each combination of external parameters such as cloud cover and surface roughness, the transition between the three regimes occurs at different values of pressure gradient. In the following a method to predict the equilibrium behaviour of the model as a function of external parameters is presented.

4. ANALYTICAL ANALYSIS

Our symplified system is governed by three coupled non-linear differential equations containing three unknown (internal) variables U, Ta and Ts. Analytical stability analysis of the system equilibria shows that the transitions between the three flow regimes are manifestations of two Hopf-bifurcations connecting a non-oscillatory solution (weakly turbulent case) to an oscillatory solution (intermittent case) and connecting this oscillatory solution in turn to a non-oscillatory solution (strongly turbulent case). Application of analytical bifurcation theory results in a dimensionless parameter (denoted with Pi), which is a function of the external model parameters such as air emissivity, cloud cover and surface roughness. By evaluation of this dimensionless parameter, the occurence of a Hopf-bifurcation in the model can be predicted. Thus the equilibrium behaviour of internal model variables (i.e. oscillating or non-oscillating), can be predicted from the evaluation of the external parameters. Due to the very complex structure of this dimensionless parameter (i.e.over one page length) , its detailed form is not presented here. The exact form will be reported in Van de Wiel et al. (2002b). It can be shown that the critical value of Pi is equal to the numerical value one. Thus, the equilibrium solutions of the model can be devided in:

$Pi < 1$; oscillatory equilibrium behaviour
$Pi \geq 1$; non- oscillatory equilibrium behaviour

5. COMPARISON OF ANALYTICAL AND NUMERICAL RESULTS

In Fig. 4, for a typical situation, the value of Pi is shown as a function of the pressure gradient (other external parameters constant). Our analytical analysis reveals that a transition in flow behaviour is expected at Pi=1. In case of Fig. 4, Pi equals 1 for two different values of pressure gradient. This means that, if the pressure gradient is gradually increased from low to high values, two transitions in flow behaviour are expected.

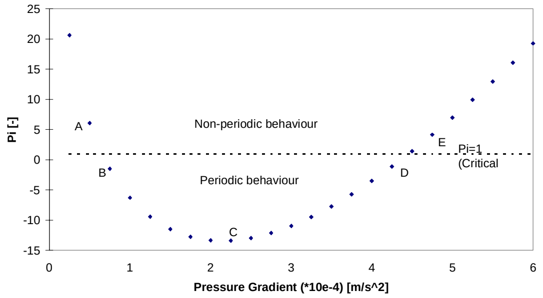

Figure 4: Dimensionless value of Pi as a function of the applied pressure gradient.

In Figs. 5a and 5b, the results of five numerical runs (A to E) are shown, corresponding to five different values of pressure gradient as depicted in Fig. 4.

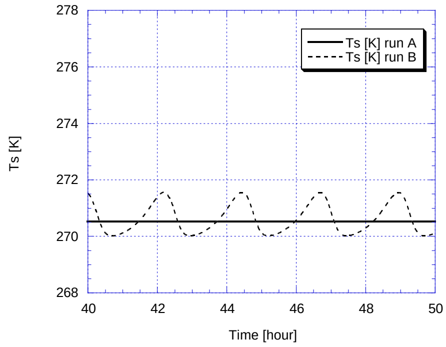

Fig. 5a: Surface temperature in an equilibrium situation for different values of pressure gradient

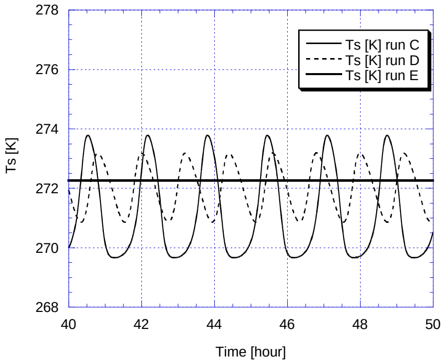

Fig. 5b: Surface temperature in an equilibrium situation for different values of pressure gradient

A comparison of Figs.5a and 5b with Fig. 4, learns that indeed there seems to occur a transition in flow behaviour at two positions as was predicted independently by the analytical model. Several hundreds of additional runs were made, varying all other external parameters. For all cases this again resulted in oscillating behaviour for $Pi < 1$ and non-oscillating behaviour for $Pi \geq 1$.

6. SBL CLASSIFICATION

We propose to use the dimensionless Pi parameter as a classification parameter dividing equilibrium behaviour in: oscillatory behaviour ($Pi < 1$) and non-oscillatory behaviour ($Pi \geq 1$).

Two important parameters determining the equilibrium model behaviour are the pressure gradient and the IsoThermal net Radiation (ITR). The isothermal net radiation is defined as the net radiation which *would* occur at the surface when the surface layer is isothermal, i.e. Ts=Ta (Holtslag and De Bruin 1988). It is the maximum value (in absolute sense) for the net radiation that may occur in the SBL and is determined by the emissivities of the surface and the atmospher. As an illustration in Fig. 6 the dependende of Pi on the ITR (for convenience the fraction of cloud cover corresponding to the ITR values are given) and the pressure gradient is given in a *contour* plot.

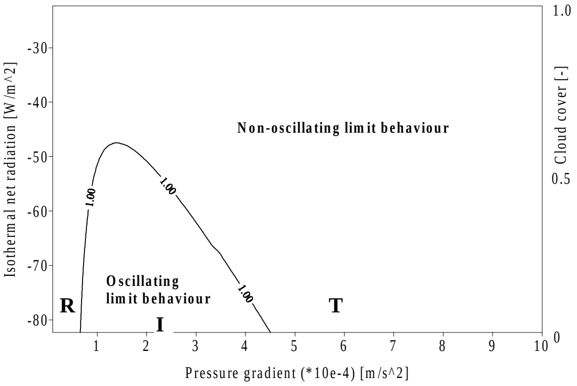

Figure 6: Contourplot of Pi =1 as a function of pressure gradient and isothermal net radiation
All points within the contour line Pi=1 correspond to the oscillatory cases.

In Fig. 6 it is seen that, up to a certain level of moderate ITR, three regimes exist cf. section 3. In fact the oscillating regime appears to split a single regime of non-periodic flow. Because Pi depends on *all* external parameters, the shape of Fig. 6 also depends on the other external parameters. Sensitivity analysis shown that the, surface roughness, the boundary layer heat and the soil heat capacity are important parameters determining the equilibrium behaviour.

7. OBSERVATIONS

In Fig. 7 an example of intermittent turbulence is given. The intermittent turbulence (sonic 5 min. avg.) was observed on a clear night (4/5 Oct. 1999) by the Wageningen University Group during the extensive field campaign CASES99, Kansas (Poulos et al. 2002). From Fig. 7 it occurs that both the amplitude and the period of the turbulent periods show an irregular behaviour. Some turbulent events have an amplitude of 5 [W/m2] and a duration of 30 minutes, others an amplitude of 25 [W/m2] and a duration of 4 hours.
It was found that the amplitudes and duration of turbulent and the quiet periods simulated by the model are comparable to the typically observed amplitudes and periods (compare Figs. 7,8 and 3).
Of course, in each modelled case the exact periods and amplitudes depend on the particular values of the imposed external variables. Due to the simplicity of the model (e.g. homogeity, stationarity of external variables) the modelled flux pattern is purely regular,

contrary to the observed fluxes, which show variation in periods and amplitudes.

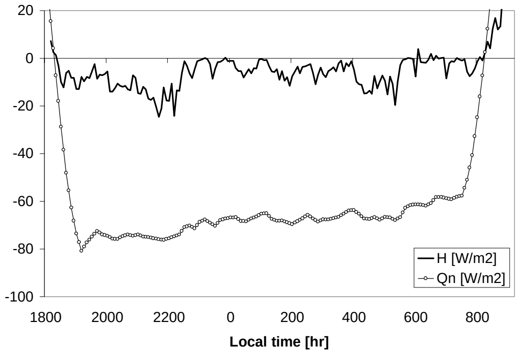

Figure 7: near-surface turbulent heat flux and net radiation on 4/5 Oct.,CASES99.

An interesting result is given by the net-radiation graph in Fig. 7. As expected the (abs. value) of the net radiation decreases during the night due to the strong surface cooling, which dimishes the outgoing longwave radiation. However, superimposed on this general trend the net-radiation shows small oscillations.

From Fig. 7 it appears that the oscilations are highly correlated with the fluctuations of the turbulent heat flux. The oscillations in the net-radiation are a direct consequence of oscillation in the surface temperature. These oscillations of the surface temperature in turn affect the stability of the near surface atmosphere leading to an important feedback mechanism between radiation and turbulence (section 1).

For the whole period of CASES99 (1month, Oct. '99) we classified the behaviour of near surface turbulence using time series of the sensible heat flux and net-radiation as in Fig. 7 (in combination with time-series of the surface stress). It occurred that the observations could be classified in three sub-classes/regimes (Fig. 8):

1) A continuous turbulent regime
2) An intermittent regime
3) A radiative regime

To give an impression of the frequency of occurrence: from the set of 27 nights **9** were classified as continuous turbulent, **6** as intermittent, **4** as radiative and 8 nights did not show a clear single regime (often transitions between the different regimes), or had incompleet data. Remark: due to the fact that a large number of nights had clear-sky conditions the number of intermittent and radiative nights is rather high. The few cloudy nights showed continuous turbulent behaviour. The existence of three subclasses/regimes in the observations agrees (at least qualitatively) with the predictions of the simplified model.

In order to interpret the observations of Fig. 8 in terms of the classification of Fig. 6, we plotted the three observed cases in Fig. 6 by (R)adiative, (I)ntermittent and (T)urbulent. Because only clear-sky cases were shown, they appear in the lower part of the graph. Apart from this preliminary qualitative comparison the authors are currently carrying out a *quantitative* comparison between the model predictions and the observations.

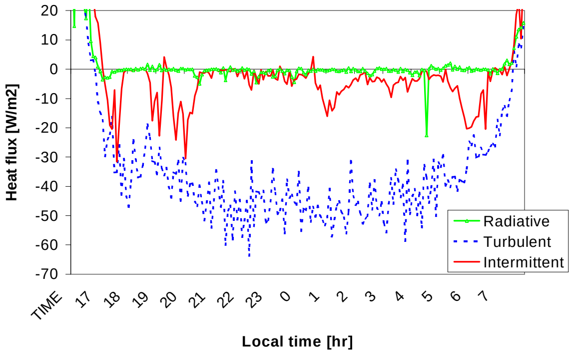

Figure 8: near-surface turbulent heat flux on three clear-sky nights during CASES99.

8. CONCLUSIONS AND RECOMMENDATIONS

1) We conclude that the intermittency mechanism as described in section 1, can be explained from a system dynamics point of view as a Hopf bifurcation connecting an oscillatory and non-oscillatory state of the system. This property can be used in predicting the equilibrium behaviour of the system.
2) The theoretical framework predicts the existence of three regimes, with decreasing pressure gradient: a continuous turbulent regime, an intermittent regime and a radiative regime.
3) Observations seem to confirm the existence of three regimes.

Both observational and theoretical work are in progress, in order to study the intermittency mechanism described in this text. The model assumptions and restrictions need further attention with respect to their theoretical and practical consequences. Finally, to get a better picture of intermittent turbulence occuring in the SBL, the possible interaction of near-surface intermittency with other processes such as wave formation and with turbulence produced by elevated shear layers, needs to be investigated.

8. REFERENCES

Businger, J. A., 1973. *Workshop on the Planetary Boundary Layer*, D.A. Haugen Ed., Amer. Meteor. Soc., 67-98.

Holtslag, A. A. M., and H. A. R. de Bruin, 1988. *Bound. Layer Meteor.,* **27**, 689-704.

McNider, R. T., D. E. England, M. J. Friedman, and Shi, X., 1995. *J. Atmos. Sci.* **52**, 1602-1614.

Poulos et al. 2002. *Bull. Am. Met. Soc., in press.*

Revelle, D. O., 1993. *J. Applied Met.*, **32**, 1169-1180.

Van de Wiel, B. J. H., R. J. Ronda, A. F. Moene, H. A. R. De Bruin, and A. A. M. Holtslag, 2002: Intermittent turbulence and oscillations in the stable boundary layer over land :
-Part I: A bulk model. *J. Atmos. Sci.* **59**, 942-958.
-Part II:A symstem dynamics approach. *J. Atmos. Sci., in press.*