13A.3 FURTHER EXAMINATION OF THE POSSIBLE ROLE OF OROGRAPHICALLY INDUCED WAVE DRAG IN THE STABLE BOUNDARY LAYER DURING CASES99

G.J. Steeneveld*, C.J. Nappo+, and A.A.M. Holtslag*
*Wageningen University, Wageningen, Netherlands. +CJN Research Meteorology, Knoxville, TN.

1. INTRODUCTION & BACKGROUND

The atmospheric stable boundary layer over land (SBL) develops after sunset (especially for clear nights) due to radiative cooling. In the special regime where the mechanical forcing (pressure gradient) and radiative cooling are of relative equal importance, so called global intermittent turbulence, and oscillations of wind speed (*U*) and temperature (θ) can be observed (e.g. Nappo, 1991; Van de Wiel et al., 2003; Acevedo et al., 2003). This is shown in Fig 1 for the surface sensible heat flux for the night of 23-24 Oct. during the CASES-99 experimental campaign in (Poulos et al., 2002). Periods with a large flux alternate with periods without any flux. This effect has not been incorporated in NWP models, and this misrepresentation may contribute to the poor model performance of these models for the SBL (e.g. Dethloff et al., 2003).

Despite intermittent oscillations are often observed, the physical mechanism behind them is unknown. Businger (1973) explains that increased stratification limits turbulent mixing, which then causes a flow acceleration aloft, and recouples the flow to the surface, and reinitiating turbulent friction. Alternatively, Nappo (1991) found that gravity waves alter the local Richardson number temporary below its critical value, temporarily allowing for turbulence.

As an alternative explanation, we examine the role of *orographically induced* gravity wave drag on the SBL (e.g. Chimonas and Nappo, 1989) and on intermittency in particular. In the linear theory, gravity wave propagation occurs for a Scorer parameter $L^2 = N^2/U^2 > k_s^2$, with stratification *N*, and terrain wave number (k_s).

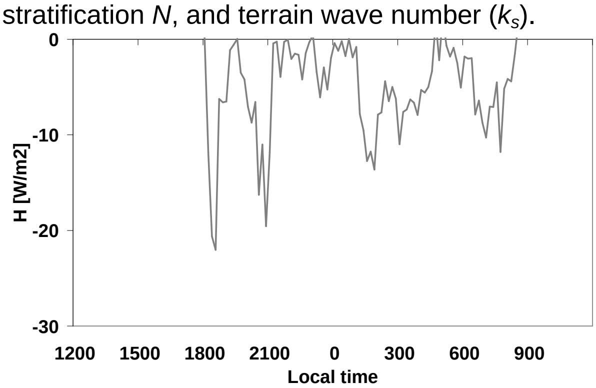

Fig. 1: Observed surface sensible heat flux for the night from 23/24 Oct 1999, during CASES99.

1 Corresponding author address: G.J. Steeneveld, Wageningen Univ., Meteorology and Air Quality Group, P.O. box 47, 6700 AA Wageningen, The Netherlands. E-mail: Gert-Jan.Steeneveld@wur.nl

We hypothesize that a sudden onset of (not turbulent) wave drag occur when $L^2 > k_s^2$, will alter the total surface friction, which then alter (via the wind speed) the turbulent friction. As such this may serve as an alternative explanation of observed intermittency.

2. SET-UP OF THE EXPERIMENT

We perform a model study on wave drag for CASES-99, aiming on the identification of wave stress 'events'. The single column model of Duynkerke (1991) is used to forecast the ABL wind speed and temperature profiles. This model has been validated against Cabauw tower observations and contrasting days in CASES-99 (Steeneveld et al., 2006), and showed good performance for the SBL, *except* for oscillations and intermittent turbulence.

The column model utilizes a 1st order turbulence scheme, with flux profile relations (with α= 0.8, β_m= 5, β_h=7.5):

$$\varphi_X(\zeta) = \frac{kz}{X_*}\frac{\partial X}{\partial z} = 1 + \beta_X \zeta \left(1 + \frac{\beta_X}{\alpha_X}\zeta\right)^{\alpha_X - 1} \qquad (1)$$

Also, a grey-body emissivity radiation scheme and a full coupling with the soil and the vegetation is applied. A logarithmically spaced grid of about 0.5 m near the surface is used, and the model runs with a time step of 10 s.

Next, the forecasted *U* and θ profiles are forwarded to a scheme that calculates the vertical profiles of wave drag (see Nappo and Svensson, 2008). Contrary to previous approaches, the scheme doesn't use a single value for the terrain amplitude and k_s (as in Steeneveld et al., 2008), but it innovatively identifies gravity wave propagation per wind sector and per Fourier mode. Wave stress contributions are then added up to the total wave drag.

The wave drag scheme uses a vertical resolution of 10 m. For now, the wave stress divergence does not feed back to the wind tendency, and we only analyze the calculated surface wave drag. To get an idea of its relative importance, calculated wave drag is compared with observed eddy covariance turbulent drag.

We made 24 hour integrations for 6-27 Oct. starting with the 1900 UTC sounding at the CASES-99 central site. Despite this region is often referred to as relative flat, Fig. 2 shows that several undulations are present in this area. The standard deviation of the terrain amounts ~7 m.

To explore the sensitivity of the wave stress to the model settings, we vary the heat conductance Λ ($Jm^{-2}K^{-1}$) between the soil and the vegetation, and the coefficients in Eq. (1).

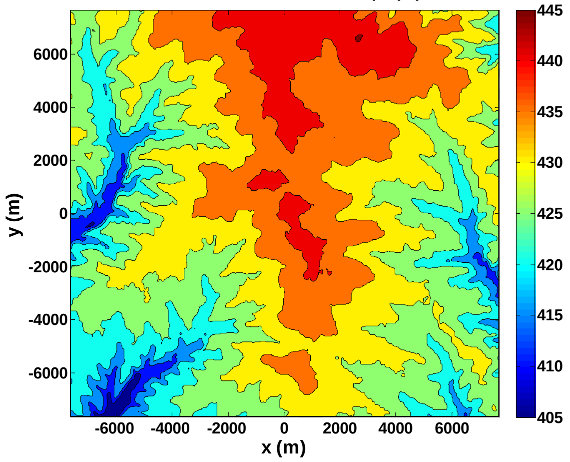

Fig. 2: Terrain height (m) of the CASES-99 terrain (central site is in the middle).

3. RESULTS

a) Individual nights

Next we will discuss the time series of calculated surface wave drag. Below we have selected some interesting nights with considerable wave stress. For each night the classification by Van de Wiel et al. (2003) for that night is mentioned (i.e. *Turbulent, Intermittent, Radiative* or *Non*).

The intermittent night from 19-20 Oct. shows intermittent behavior of wave stress, with typically a time scale of 1-2 h (Fig. 3a). Also, the calculated magnitude of the wave stress events corresponds to the magnitude of the turbulent drag. Since the wind and temperature fields from the column model do not show any intermittency, the intermittent wave drag is generated completely *independently* by the wave module, and the consequence of the interaction between the SBL flow and the orography. As such it confirms our hypothesis.

For the night of 20-21 Oct. we find that the wave drag is mostly active just in the transition (Fig 3b). Although not shown here, we found that nights with negligible mean wave stress do show some strong peaks in wave stress after the transition. This occurs for the night 11/12, 18/19, 23/24, and 26/27 Oct.

Despite the wave stress is not intermittent for the night of 9-10 Oct., the night is interesting in the series we discuss here. This night has only a geo-strophic wind speed of about 2.5 ms^{-1}, and the observed turbulent fluxes are extremely small. However, Fig. 3c shows that the modelled surface wave drag is substantial, and that its magnitude is as large as the turbulent flux. Finally, Fig. 3d shows the model results for the radiative night from 25-26 Oct in which the turbulent fluxes vanish. Then also the wave stress is zero since $L^2<0$.

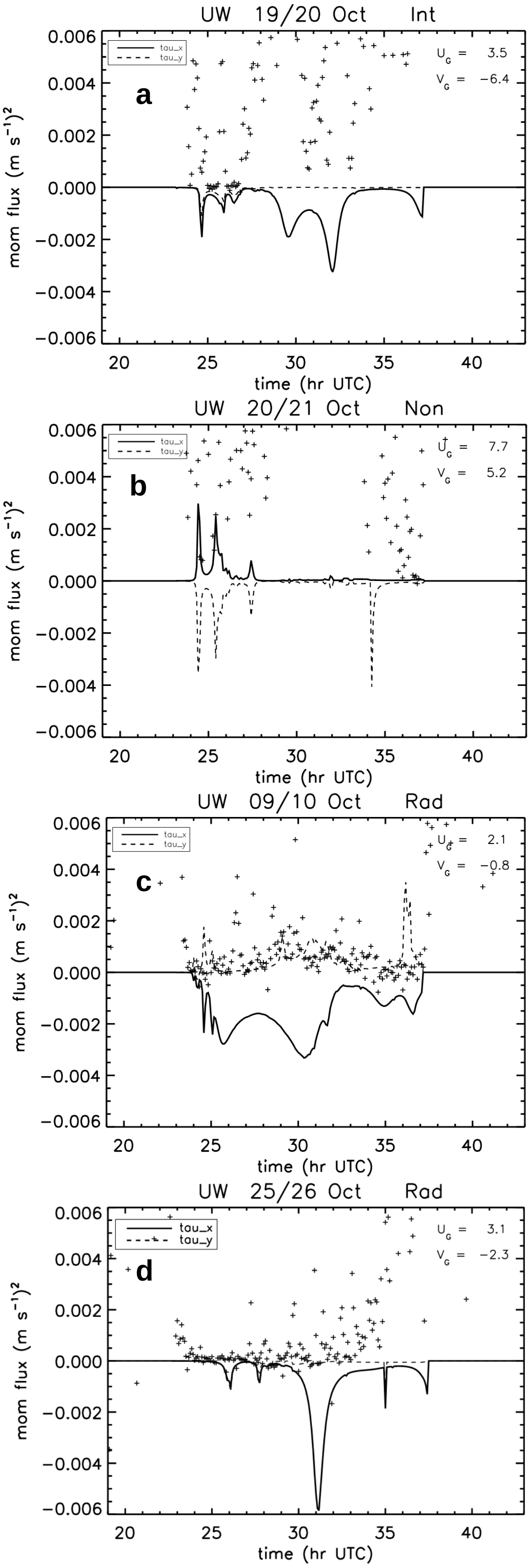

Fig 3: Modelled surface wave stress components (lines), and measured turbulent stress (+) for a series of nights in CASES-99. In the header the classification of Van de Wiel et al. (2003) (Turb, Rad, Non) is also indicated, (U_g,V_g) indicate the geostrophic wind for the simulation.

However, at the end of the night, the near surface wind speed increases, and it generates both turbulent stress and wave stress of comparable magnitude.

In addition to the intermittent behaviour of the wave stress, we also find in general that the magnitude of the wave stress is larger for the x direction than for the y direction. This is due to the fact that in general the terrain wavelength is larger in the x direction than in the y direction, and thus $L^2<0$ is more often fulfilled in the y direction.

b) Sensitivity to surface interaction

We may hypothesize that the calculated wave stress depends on the near surface wind and stratification, that is strongly governed by coupling between soil and vegetation. As such we ran the model for Λ =5.9 (as previously reported), and for Λ = 4.5 as an alternative.

Fig. 4 shows the results for night 9-10 Oct. Intercomparing the results with Fig. 3c, we find that low Λ results in a similar amount of wave stress, except that in the early night more events occur, although their numerical value is small.

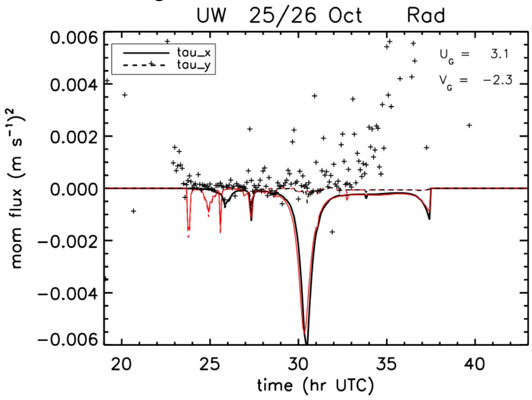

Fig 4: Modelled surface wave stress components (lines), and measured turbulent stress (+) *for 25/26 Oct. in CASES-99.Black = original* Λ *=5.9, Red* Λ*=4.5.*

c) Sensitivity to profile functions

Since the wave propagation is triggered by the θ and *U* profiles, one may expect a certain sensitivity to the chosen form of the flux-profile relations in the ABL model. Fig 5 shows the results the modification for β_h=β_m=4 in Eq. (1). Our general finding is (also for other nights, not shown) that the functional form of the flux-profile relations provides a time shift of the wave stress events, but only slightly alters the wave stress magnitude. This robustness of the results provides further confidence in the relevance of the mechanism.

4. DISCUSSION

Some aspects of the above results need further attention. First of all, the coupling of the column model and the wave stress module is non-trivial. One may question what is the appropriate surface wind speed to force the wave module. For the real surface wind (i.e. 0 ms^{-1}) no wave stress will occur. For wind speed higher in the boundary layer, wave stress does occur, but one should question whether this is really the wind speed that is felt by the orography. Belcher and Wood (1996) propose that the wind speed at the 'middle layer height' gives the best results compared to detailed model simulations.

Next the link between wave drag and intermittency of turbulence needs further research. The current simulations provide only a mechanism that generates surface wave drag, but wave breaking or dissipation is needed to provide feedback on the wind speed. This has not incorporated yet. However, Nappo and Svensson (2008) did incorporate this and found substantial wave stress divergence, and as such the current results are promising.

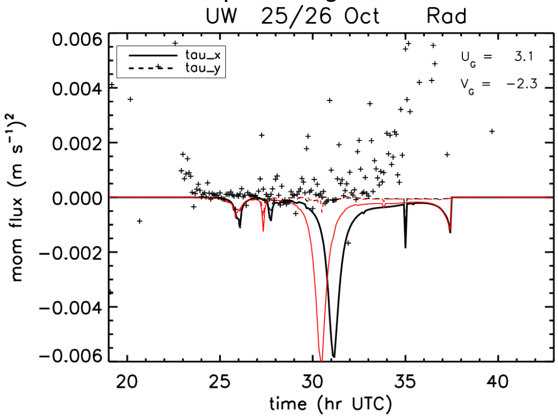

Fig 5: Modeled surface wave stress components (black β_h=β_m=5; red: β_h=β_m=4*) for different profile functions (see text), and measured turbulent stress* (+) *for 25/26 Oct. in CASES-99.*

5. CONCLUSIONS

This paper analyzes the role of orographically induced wave drag on intermittency and oscillations in the stable boundary layer. It is found that for relatively weak winds, the surface wave drag is intermittent on a timescale that corresponds to intermittency in observations. Although this is not a final explanation of intermittency, it may contribute to further understanding of the phenomenon.

Furthermore, it is realized that the wave stress is relatively large compared to turbulent surface stress in calm nights.

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