Analysis of WRF-Simulated Thermally Diurnally Periodic Boundary-layer Wind Signals in Eastern China

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Introduction

Diurnal variation of the boundary-layer winds in eastern China is a prominent feature of coastal regions, where land-sea temperature gradients exist, or near mountains, where slope flows are prevalent (Fig. 1a). Hourly model data (9-km horizontal resolution and 40 vertical levels) for the period June 2006-2011 simulated with WRF from 12-36h simulations of each day (Du et al. 2014, Du Model Data), verified against long-record observations, are used to study the low-level diurnal winds at different locations (Points A-D in Fig. 1b) of eastern China and the characteristics of thermally driven diurnally periodic wind signals off the east coast of China (green boxes in Fig. 1b).

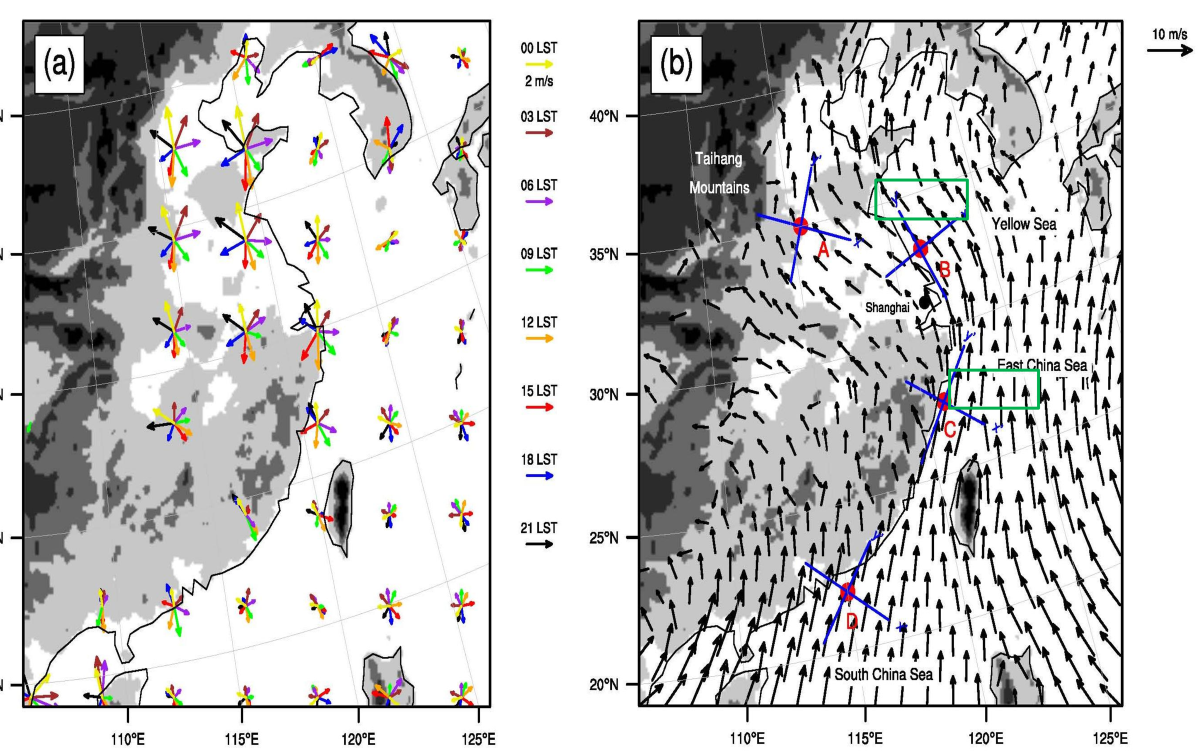

Fig.1 Horizontal distribution of (a) diurnal cycle of the perturbation wind vector at 3-h intervals and (b) diurnal mean wind vectors at the 950 hPa height for June from 2006-2011 with terrain height (shading, m) and locations A, B, C, D with the local rotated Cartesian coordinates used in the present analysis. Two green boxes are used for the analysis in Fig. 3a-b

2. Analysis of the Diurnal Winds with a Simple 1D Model

- In northeastern China, at similar latitudes, the maximum velocity parallel to mountains over land (point A, 0200 LST) occurs later than the maximum velocity parallel to the coastline over the ocean (point B, 2100 LST). **Why?**

- Off the east coast of China, the maximum velocity parallel to the coastline at high latitude (point B, 33N) occurs earlier than that at low latitude (point C, 27.5N). **Why?**

- The amplitude of the diurnal wind off the south coast (point D, 22N) is much weaker than that off the east coast (point C, 27.5N) **Why?**

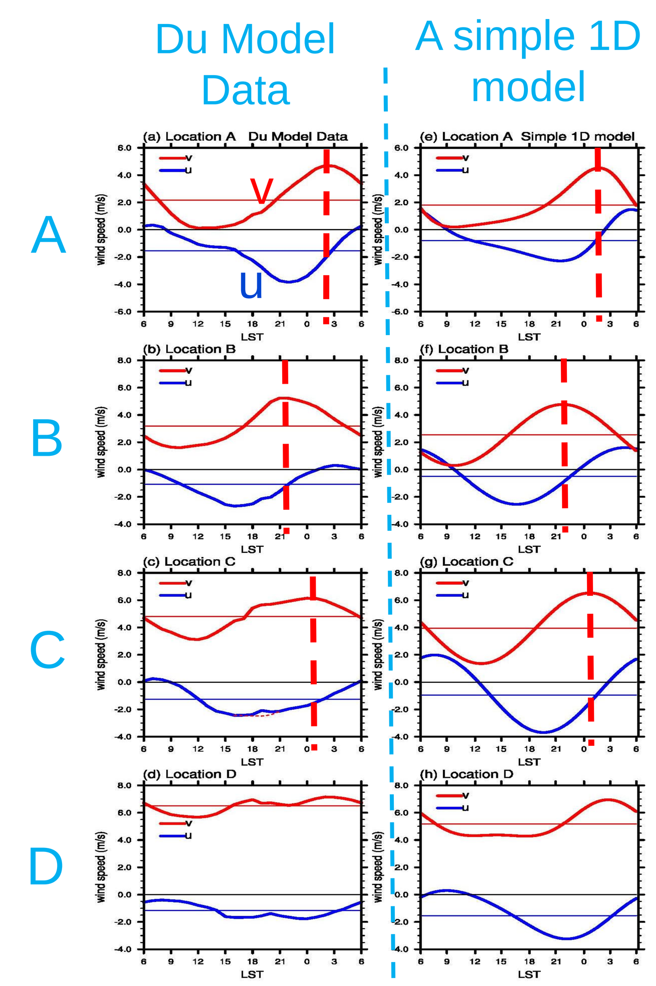

Fig.2 Diurnal variations of mean 950-hPa local u- and v- wind component at locations A, B, C and D from the Du Model Data (a-d) and the simple 1-D model (e-g) with mean values indicated by the thin solid lines

- **Review of Du-Rotunno 1D model**

Du and Rotunno (2014) studied the formation mechanism of the LLJ over the Great Plains of U.S. using the one-dimension linear equations of motion for frictional flow on an f- plane. After nondimensionalizing the equations, analytical solutions were obtained for

- Holton (constant friction with diurnally varying pressure gradient)
- Blackadar (diurnally varying friction with a time-independent pressure gradient)
- Combination.

$$\begin{cases} \dfrac{\partial u}{\partial t} - fv = -\dfrac{1}{\rho}\dfrac{\partial P}{\partial x} - \alpha u \\ \dfrac{\partial v}{\partial t} + fu = -\alpha v \\ -\dfrac{1}{\rho}\dfrac{\partial P}{\partial x} = \overline{F} + \hat{F}\cos\omega t \end{cases}$$

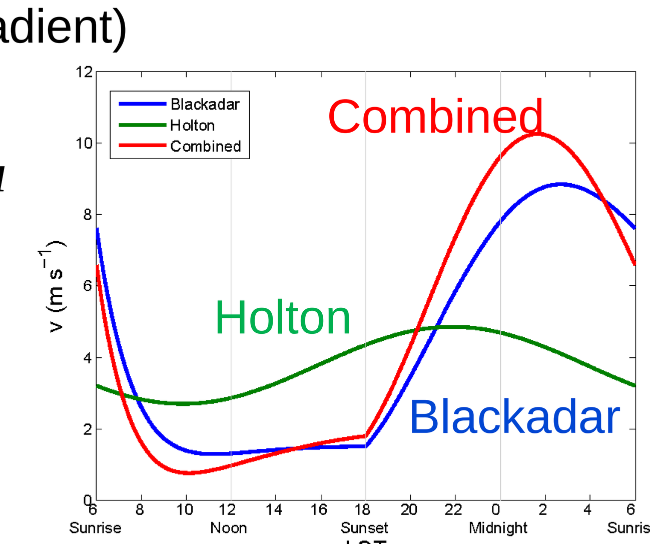

Fig.3 Comparison of the diurnal variations of among the Holton mechanism (green), the Blackadar mechanism (blue) and their combination (red)

- Because Blackadar mechanism plays a significant role over land.

- According to 1D model, land-sea breezes have very different diurnal cycles depending on whether the latitude is greater or less than 30N ($f=\omega$).

Holton solution $\tilde{v} = -\dfrac{\bar{\varepsilon} f\omega}{\alpha^2 + f^2} - \dfrac{\hat{\varepsilon} f\omega}{\sqrt{\left(f^2+\alpha^2-\omega^2\right)^2 + 4\alpha^2\omega^4}}\sin(\omega t+\psi)$ $\psi = \tan^{-1}\left(\dfrac{f^2+\alpha^2-\omega^2}{2\alpha\omega^2}\right)$

- The amplitude of the diurnal variation of v decreases with decreasing latitude.

3. Diurnally Periodic Wind Propagation Signals off the Coast

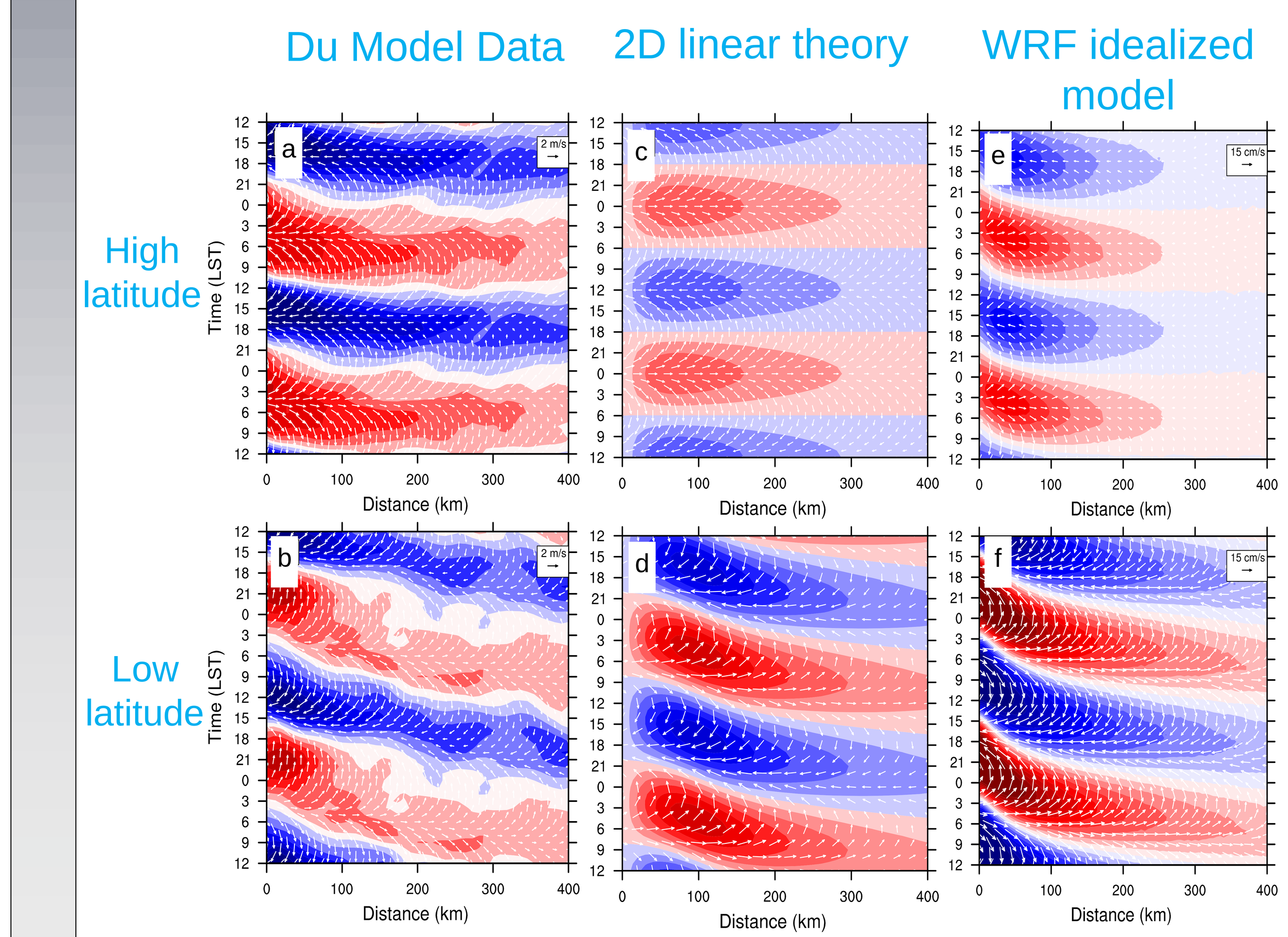

Fig.4 Longitude-time Hovmöller diagrams of perturbation horizontal wind vectors and vertical velocity at 950 hPa averaged (shaded; m s^{-1}) over the a) northern and b) southern boxes in Fig. 1b from the Du Model Data; the present linear solutions at c) 35N and d) 25N; idealized WRF experiments with terrain and surface heating at latitudes e) 35N and f) 25N.

- Low-level diurnally periodic wind signals propagate eastward off the southeast coast whereas diurnal wind variations off the northeast coast are nearly in phase. (Figs. 4a and 4b)

- **2D linear model land-sea breeze model**

$$\begin{cases} \dfrac{\partial u}{\partial t} - fv = -\dfrac{\partial \phi}{\partial x} - \alpha u \\ \dfrac{\partial v}{\partial t} + fu = -\alpha v \\ \dfrac{\partial w}{\partial t} - b = -\dfrac{\partial \phi}{\partial z} - \alpha w \\ \dfrac{\partial b}{\partial t} + N^2 w = Q_0\left(\dfrac{\pi}{2} - \tan^{-1}\dfrac{x}{x_0}\right)e^{-z/z_0}e^{-i\omega t} \\ \dfrac{\partial u}{\partial x} + \dfrac{\partial w}{\partial z} = 0 \end{cases}$$

$$w \sim e^{-(\cos\varphi - i\sin\varphi)x}$$

$$\varphi = \frac{1}{2}\left(\frac{\pi}{2} - \tan^{-1}\frac{f^2-\omega^2+\alpha^2}{2\omega^2\alpha}\right)$$

When α=0 $\begin{cases} w \sim e^{-z} \text{ when } f > \omega & \textbf{Trapped-like} \\ w \sim e^{-iz} \text{ when } f < \omega & \textbf{Wave-like} \end{cases}$

The simple 2-D linear land-sea-breeze model with friction can capture this main difference in propagation character with respect to latitude. (Figs. 4c and 4d)

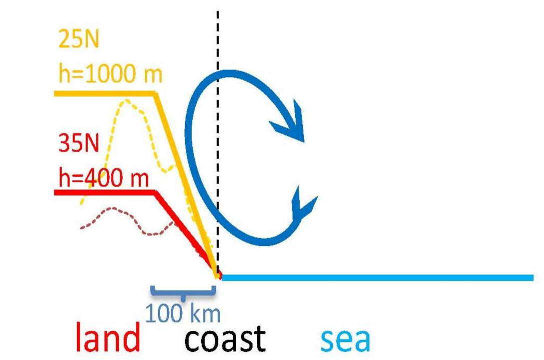

Fig. 5 A schematic diagram showing the circulation near the coast with terrain for two terrain profiles used (yellow-25N, red-35N; solid lines represent the terrain used in the idealized model; dashed lines represent the terrain from the Du Model Data).

- Idealized 2D simulations using WRF that includes surface heating and terrain are found to explain certain features not captured by the present linear theory. (Figs. 4e and 4f)
  - Due to heat transport from the surface, WRF idealized model has a phase lag with respect to the linear model that brings the absolute time phase closer to that from the Du Model Data.
  - With coastal terrain in the idealized model the maximum amplitude becomes located at the coast and the maximum occurs earlier at and near the coast as compared to the situation without terrain

4. Summary

- The low-level diurnal winds for different locations of eastern China are explained with the 1D simple model.

  At a similar latitude, v_{max} over the ocean occurs earlier than over land. This difference can be identified with the Blackadar effect over the land.

  Off the east coast of China, the diurnal winds for different latitudes over the ocean vary in both phase and amplitude, consistent with expectations based on the simple 1D model's Holton solutions.

- The thermally driven diurnally periodic wind propagation signals off the east coast of China, which are different between the south and north: offshore eastward propagation of the vertical motion in the boundary layer off the southeast coast of China exists while the diurnal signal in vertical motion is more phased-locked off the northeast coast of China.

5. References

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