A meteorological numerical model adapted to laboratory experiments: application to trapped orographic waves

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The CNRM-GAME hydraulic tank

Main characteristics:
- 22 m x 3 m x 1 m
- High Reynolds numbers
- Stably stratified flows (salt)

Studies:
- Internal gravity waves
- Atmospheric boundary layer

Why using a numerical model to simulate flows in the tank?
- Extension of experimental data
- Better understanding of the processes involved
**Dimensional analysis**

**π theorem**: A problem with $p$ independent variables and $n$ dimensions can be described with $p-n$ dimensionless numbers.

Dimensionless numbers

\[ R = \frac{H \cdot U}{\nu} \]

- $\nu$: Kinematic viscosity

\[ \nu_{\text{air}} \approx 10^{-6} \text{ m}^2 \cdot \text{s}^{-1} \]

\[ \nu_{\text{water}} \approx 10^{-4} \text{ m}^2 \cdot \text{s}^{-1} \]

Atmosphere $\rightarrow$ Hydraulic tank $\rightarrow$ Atmospheric model

Reynolds $\quad R_{\text{atm}} > R_{\text{lab}} = R_{\text{model}}$

$R_{\text{lab}} = 20 000 \implies \nu_{\text{model}} \approx 1 \text{ m}^2 \cdot \text{s}^{-1}$
The numerical model: Meso-NH


Configuration used: Boussinesq, no Coriolis, dry air, no surface scheme.

Adaptation of the model:

- Viscosity diffusion added:
  - Momentum: \( \nu \cdot \nabla \overrightarrow{U} \)
  - Temperature: \( \frac{\nu}{Pr} \cdot \nabla \theta \) (Pr: Prandtl number)

- Explicit no-slip condition: \( u(0) = v(0) = 0 \)
  No \( z=0 \) level for \( u \) and \( v \)

\( \Rightarrow u(-\Delta z/2) = - u(\Delta z/2) \)

So that \( \overrightarrow{U}_{K=KB} \) is as if \( u(0) = v(0) = 0 \)
No-slip condition validation with an analytical solution

First Stokes's Problem: initially still flow over a suddenly accelerated flat plate ($U_0$ speed)
Equivalent in the model: no-slip condition suddenly applied to a uniform flow ($U_0$ speed)

\[ \delta \approx 3.64 \sqrt{v \cdot t} \quad \text{with} \quad \delta \cdot u_{(z=\delta)} = 0.99 \cdot U_0 \]  
(Schlichtling, 1968)

Simulations

Explicit
$U_0 = 10 \text{ m.s}^{-1}$
$\Delta X = \Delta Y = 1 \text{ m}$
$1 \text{ m} \leq \Delta z \leq 10 \text{ m}$
No-slip condition comparison to measurements in the hydraulic tank

Development of the boundary layer (BL) on the ground of the tank (no rugosity)

Simulations:

From the dimensional analysis:
- $L = 35 \text{ km}$
- $l = 4.8 \text{ km}$
- $H = 1600 \text{ m}$
- $U_0 = 10 \text{ m.s}^{-1}$
- $\nu = 0.064 \text{ m}^2.\text{s}^{-1}$

Chosen resolution:
- $\Delta X = \Delta Y = 20 \text{ m}$
- $0.5 \text{ m} \leq \Delta z \leq 50 \text{ m}$
No-slip condition comparison to measurements in the CNRM-GAME hydraulic tank

**Data**: Development of the boundary layer (BL) on the ground of the tank (no rugosity)

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From the dimensional analysis:
- \( L = 35 \text{ km} \)
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=> 3D Turbulence scheme necessary
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Application to trapped orographic waves
Elser et al. (2007) theory

Flow controlled by:

\[ Fr = \frac{U_0}{\sqrt{g \cdot h'}} \quad \text{with} \quad h' = f(H_1, H_2) \]
\[ M = \frac{h}{H_1} \]

For \( Fr \approx 1 \), only

\[ \Gamma = (Fr - 1) \cdot M^{-2/3} \]
Laboratory experiments and model configuration

**Dimensionless numbers**

\[ R = \frac{H \cdot U}{\nu} \]
\[ Fr = \frac{U}{\sqrt{gh'}} \]
\[ M = \frac{H_1}{l} \]
\[ d = \frac{H_1}{H_2} \]

**Experiments**

- \( Fr \) from 0.5 to 1.8
- \( U_L = 123 \) km
- \( W = 23 \) km
- \( H_1 + H_2 = 2500 \) m
- \( l \approx 6500 \) m
- \( h \approx 850 \) m
- \( U \approx 20\) m.s\(^{-1}\)

**Model**

- \( \Delta \theta/\theta = -(\Delta \rho/\rho)_{lab} \)
- \( v \approx 1 \) m\(^2\).s\(^{-1}\)

- \( \Delta X = \Delta Y = 120 \) m
- \( 0.5 \) m \( \leq \Delta z \leq 50 \) m
  - (72 levels)
- 3D TKE turbulence
- No-slip on the mount
Height of the interface

\( Fr = 0.93 \)

(F. Stoop)
Drag

(F. Stoop)
Drag

(F. Stoop)
Drag

(F. Stoop)
Drag

(F. Stoop)
Effect of the boundary layer

Wind and interface behind the mount (Fr = 0.93)

Model vs. Experiment

Free-slip vs. No-slip

(F. Stoop)
Conclusions and perspectives

**Conclusions**
- Meso-NH is able to simulate laboratory experiments in a hydraulic tank
- It can be used to extent the experimental data (more thorough data, further sensitivity tests)
- The boundary layer (BL) does not seem to impact much the drag on the mount, but it can change the shape of the orographic waves (interface)

**Perspectives**
- Meso-NH: further assessments of the model's limitations
- Further work on the boundary layer's effect:
  - run other free-slip simulations to assess the BL's effect for a larger range of Froude numbers
  - evaluate its impact on the drag computed on the lee-side of the mount
- Theory: add continuous density profile, gaussian mount, elliptic mountain.
Viscosity diffusion validation with an analytical solution

\[
\begin{align*}
\bar{U}(x, y, z, 0) &= U_0 \cdot \sin \left( \frac{\pi y}{L} \right) \cdot \tilde{X} \\
P(x, y, z, 0) &= -\rho g z \\
\theta(x, y, z, 0) &= \theta_0
\end{align*}
\]

\[\Rightarrow \quad \bar{U}(x, y, z, t) = U_0 \cdot \exp \left( -\nu \frac{\pi^2}{4} t \right) \cdot \sin \left( \frac{\pi y}{L} \right) \cdot \tilde{X}\]

Simulation:

Fully explicit model (no parameterization)

\[U_0 = 10 \text{ m.s}^{-1}\]
\[\nu = 100 \text{ m}^2\text{s}^{-1}\]
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**Simulations**

Explicit

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\[\Delta X = \Delta Y = 1 \text{ m}\]
\[1 \text{ m} \leq \Delta z \leq 10 \text{ m}\]

Kolmogorov's scale: \(l\)

\[l = 0.3 \text{ m} ; \lambda = 2 \text{ m}\]

Taylor's scale: \(\lambda\)

\[l = 0.08 \text{ m} ; \lambda = 0.6 \text{ m}\]
\[l = 0.05 \text{ m} ; \lambda = 0.4 \text{ m}\]
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Chosen resolution:

$\Delta X = \Delta Y = 20 \text{ m}$
$0.5 \text{ m} \leq \Delta z \leq 50 \text{ m}$

$l = 0.08 \text{ m}$
$\lambda = 1 \text{ m}$

$\Rightarrow$ Turbulence scheme necessary
Effect of the viscosity diffusion terms

Without viscosity diffusion

With viscosity diffusion

$v=0.992 \text{ m}^2 \text{s}^{-1}$
Drag on the mountain

Drag

- Linear theory
- No-slip simulations
- Experiments
- Free-slip simulations
Drag

Shape WA of the mountain + height taken into account
Two layers are considered for the undimensional drag
Drag

Shape WA of the mountain + height taken into account
A single layer is considered for the undimensional drag