High Vertical Resolution Numerical Simulation of Summer Flows in Catalonia. Implications to Spatial and Temporal Variability of Ozone and PM10 Levels

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The aim is:

To analyze the dynamics of the sea-breeze and its effects on 3D (O_3 and PM10) pollution transport in Catalonia region.

To attain this objective we use ground based stations, a Doppler Sodar and mainly numerical simulations.

SRUCTURE OF THE TALK

1. Short introduction (pointing out the main components of the sea-breeze circulation).

2. An overview of:

- The main topographic characteristics of the studied area.
- The modelling system used and the experimental set up.

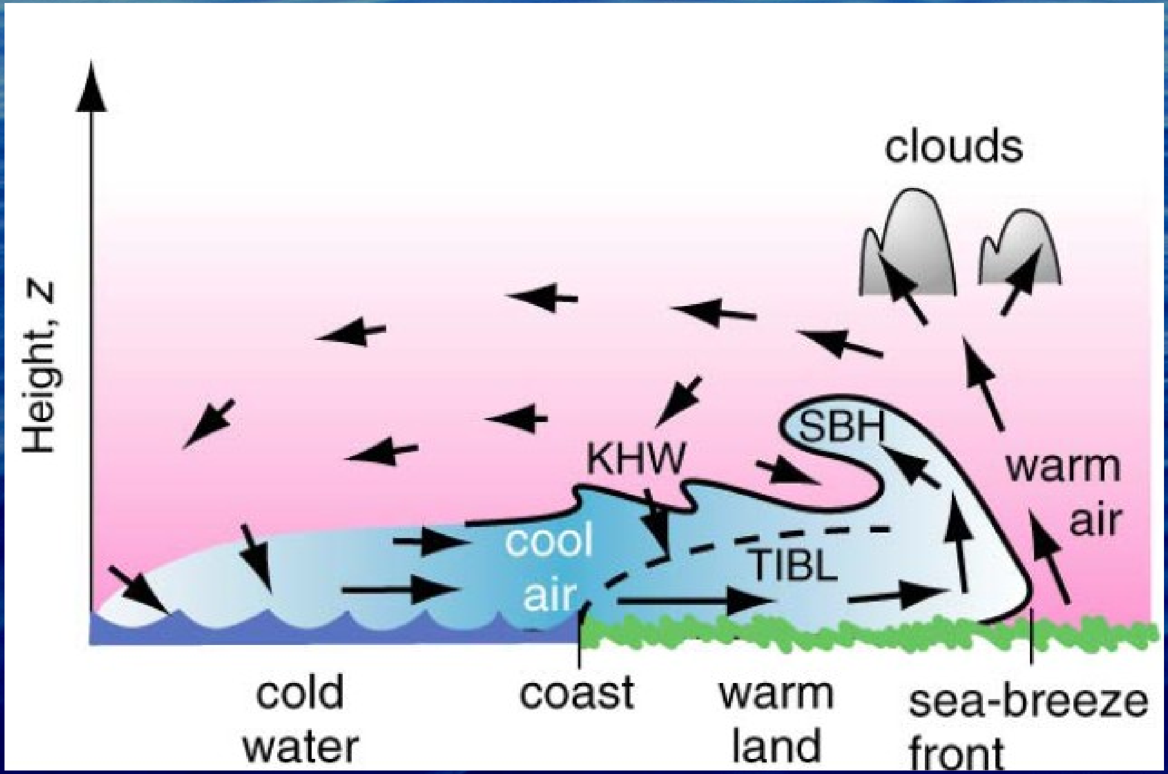
3. The sea-breeze impact on the horizontal flow field and on the vertical structure of the lower troposphere (ABL).

4. The pollutants distribution under these sea-breeze conditions.

5. Some conclusions.

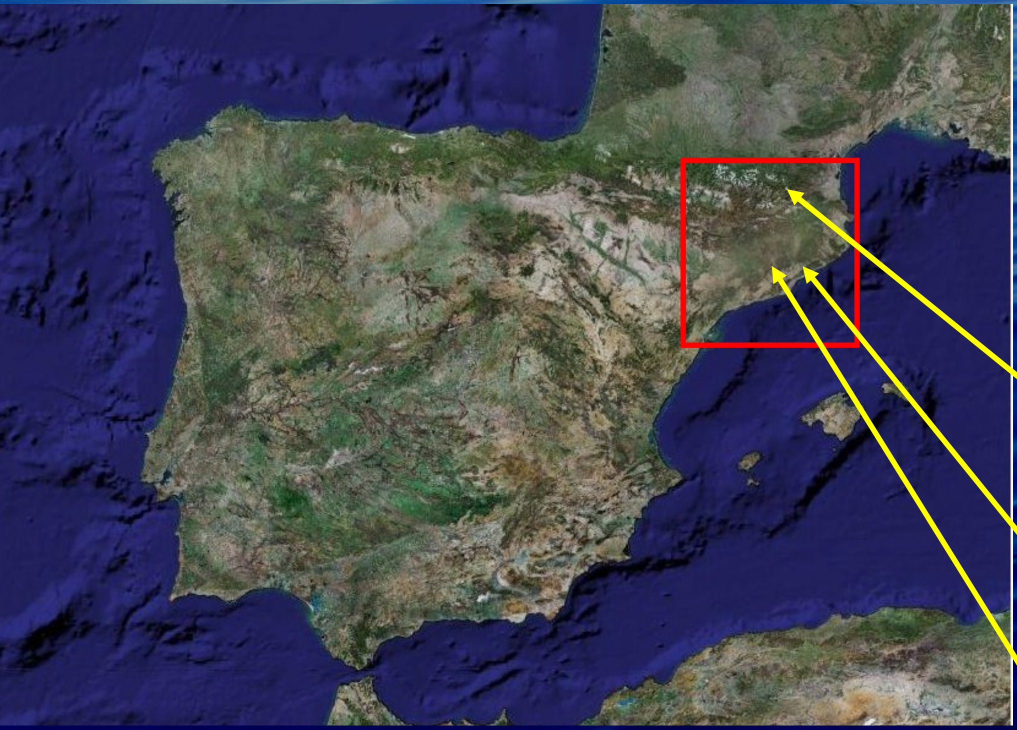
INTRODUCTION

As a brief reminder



The main idealized components of a mature sea-breeze circulation: SBH = the sea-breeze head, KHW = Kelvin-Helmholtz waves close the head region in the interface between the sea-breeze and return flow, and the thermal internal boundary layer (TIBL), dashed line shows the top. (Wallace and Hobbs, 2006, figure 9.35)

MAIN TOPOGRAPHIC CHARACTERISTICS OF CATALONIA



Catalonia is located in the NE corner of the Iberian Peninsula.

Its coastline runs in a NE–SW direction and its main topographic features are:

The Pyrenees (1500–3100 m), which run roughly W to E along the northern border of Spain.

A littoral mountain range with some peaks exceeding 500 m.

A pre-littoral mountain range with higher elevations (1000–2000) m.

MODEL SETUP AND INITIALIZATION

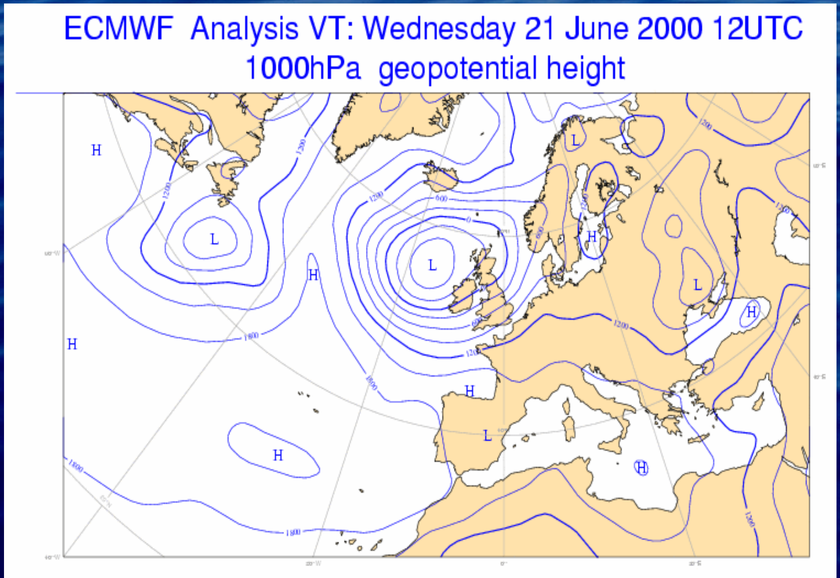
The modeling system used is the Mesoscale Meteorological MM5 coupled to CMAQ model

- Simulation period:
- 3 days long from 20-22 June 2000, although the analysis is focused on 21 June.

- The framework in larger scale

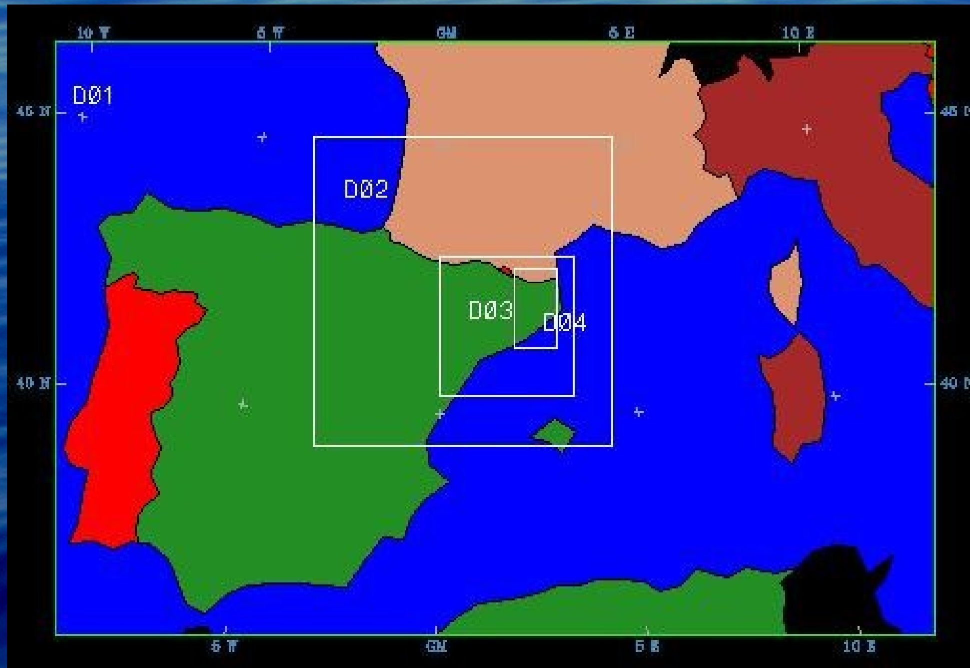
  Initial and boundary conditions were updated every 6 hours with information obtained from ECMWF model with 0.5 x 0.5 resolution

  No initial and boundary conditions are considered for CMAQ model, in order to do not mask the emissions transport of the specific source considered.



Synoptic conditions indicate weak pressure gradients in the studied area, allowing sea-breeze development.

DOMAIN SYSTEM



Domain 1 (coarse) :

- grid : 59x45
- size : 27 km

Domain 2 :

- grid : 70x70
- size : 9 km

Domain 3 :

- grid : 94x94
- size : 3 km

Domain 4 (finest) :

- grid : 91x163
- size : 1 km

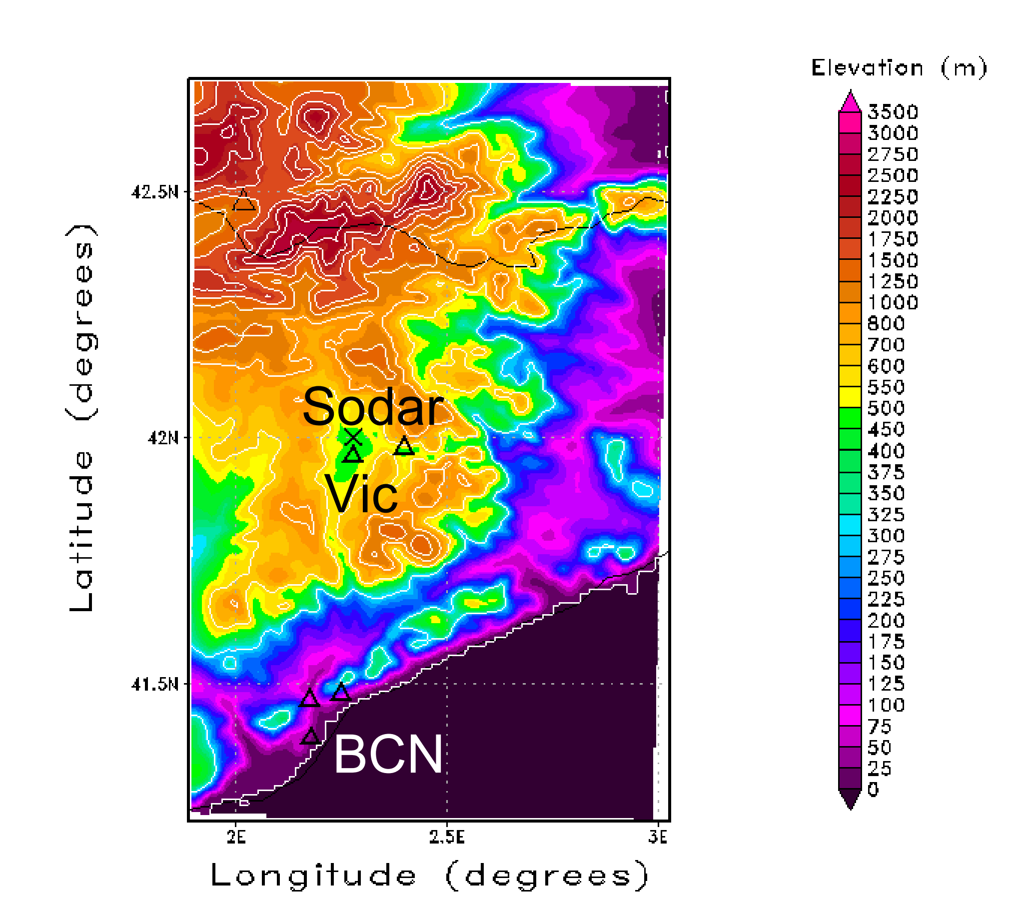
Vertical grid

- 45 grid up to 4000 m agl, resolution 10 m near the surface
- the depth is from surface to 100 hPa with 55 levels

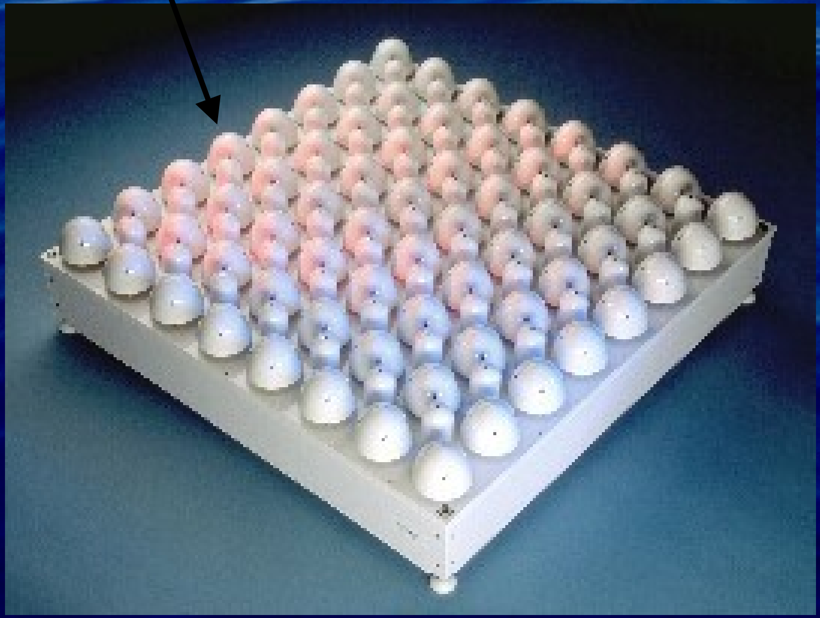
We focus our study in domain D4, because include one of the most important industrial areas of Catalonia located near the sea.

GROUND BASED MONITORING THE SEA-BREEZE

To monitoring the sea breeze, we use a Doppler Sodar and a ground station network located in the smallest domain. We select only the most representative stations, Vic (inland) and Barcelona (BCN) located in the coast.

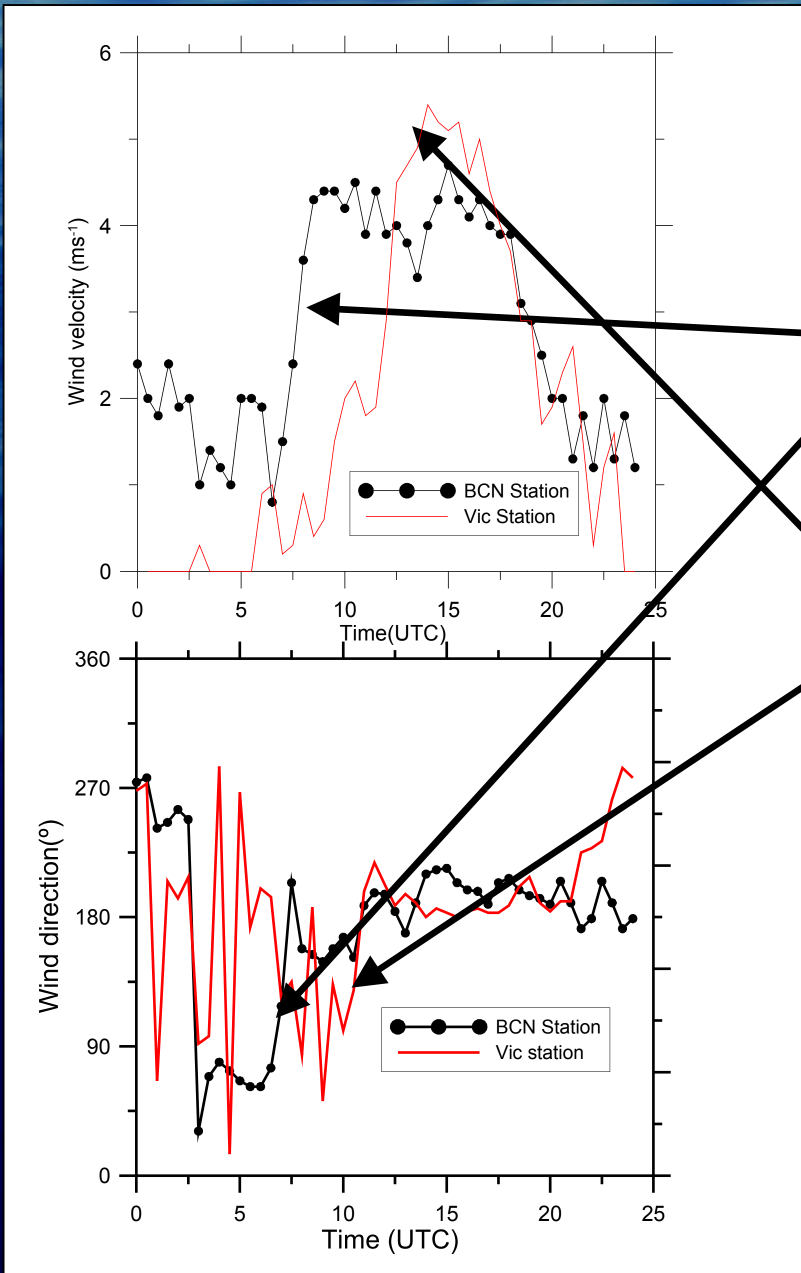


Geographic area of the smallest domain



Scintec FAS64 (phased array) Doppler Sodar

THE IMPACT OF THE SEA-BREEZE ON THE HORIZONTAL FLOW FIELD

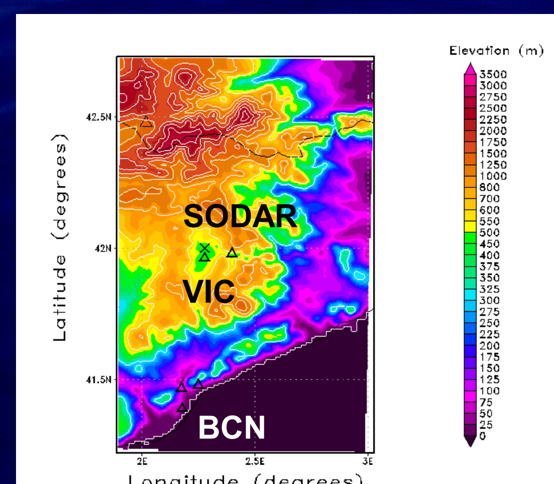


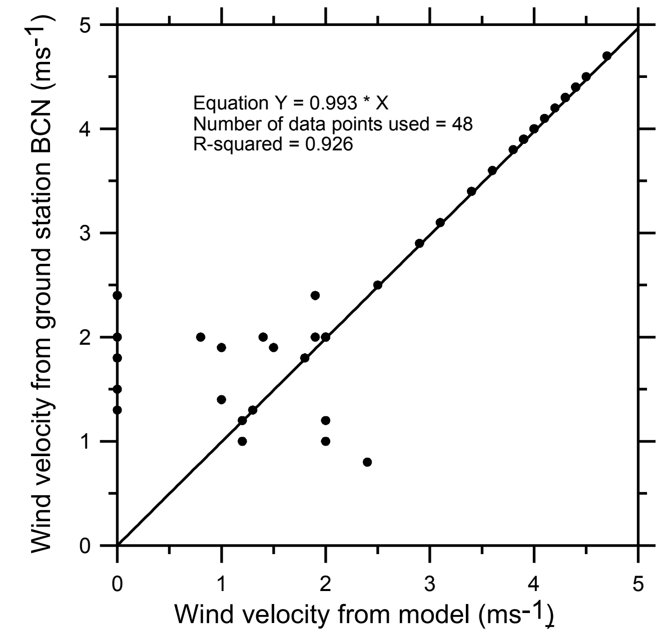
Ground based stations and model simulations

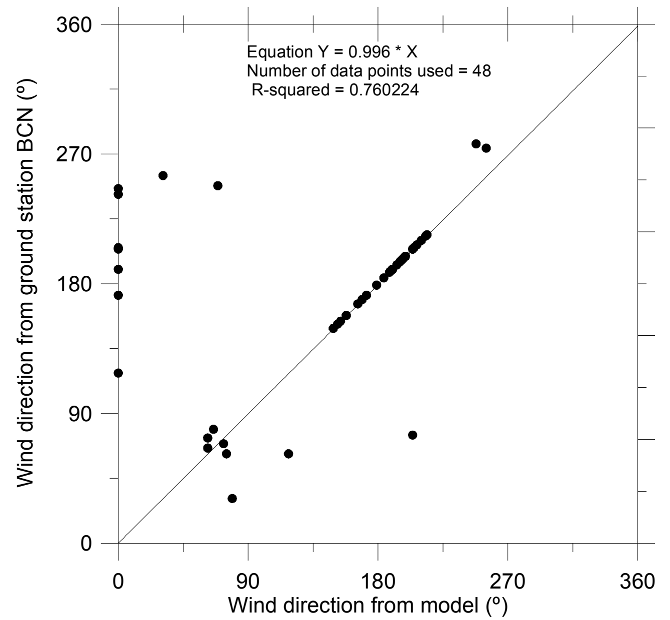
Temporal evolution of wind velocity and wind direction at Barcelona (coast) and Vic (inland).

At Barcelona, the sea-breeze onset is well detected in the early morning by a strong increase in W-V and abrupt change in W-D from NE to S sector.

At Vic station (60 km inland) the sea breeze onset is later, at 1300 UTC approximately with almost the same characteristics.

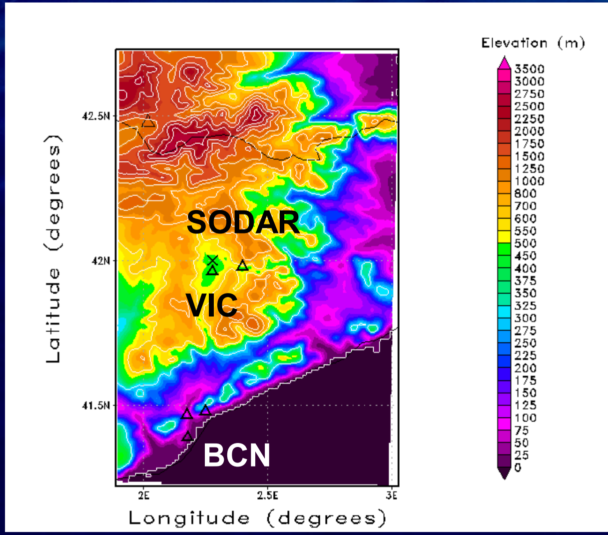


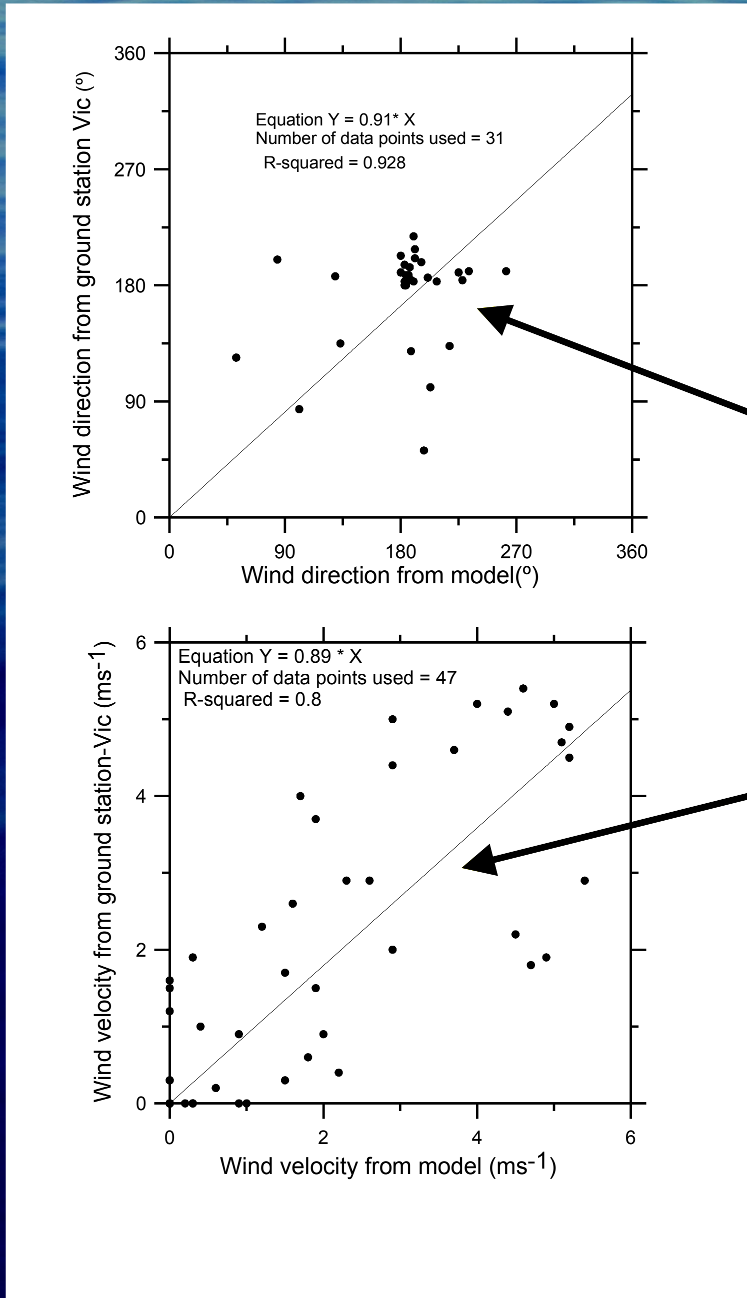




To study the model capability to simulate the sea-breeze, we compared model simulations with observations.

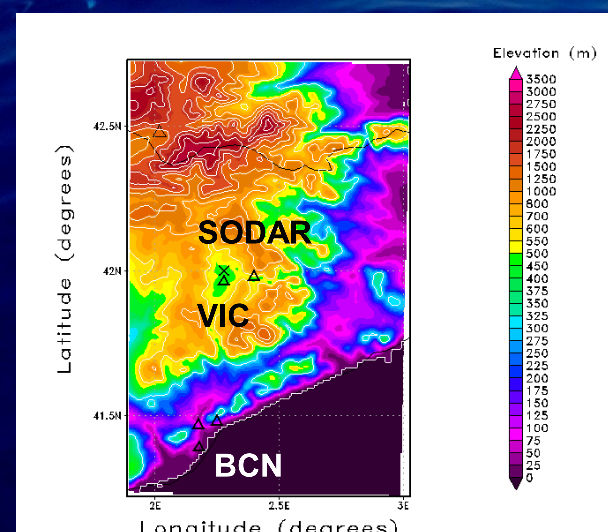
At Barcelona station, simulated wind velocities and directions are in good agreement with observations, especially for high velocities and wind coming from the south sector corresponding to the sea-breeze.



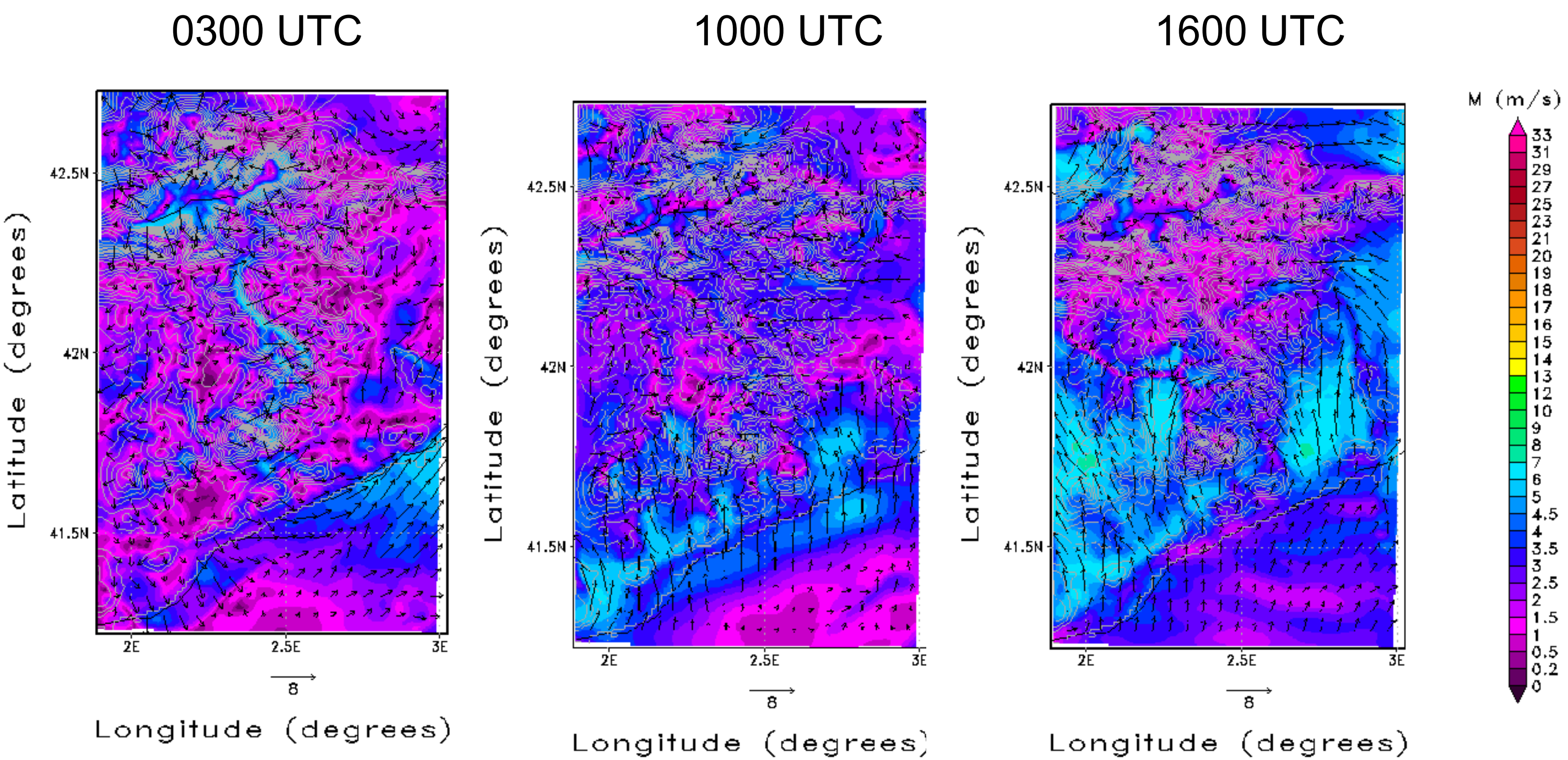


At Vic station, wind direction comparison was made filtering wind velocities lower than 0.5 ms-1, since the wind directions in these conditions were unreliable.

Comparison results show good agreement for wind direction especially those coming from south sector which corresponds to the sea-breeze. The correspondence is remarkably worse for wind velocity.



SIMULATED HORIZONTAL WIND FIELDS AT 10 m agl

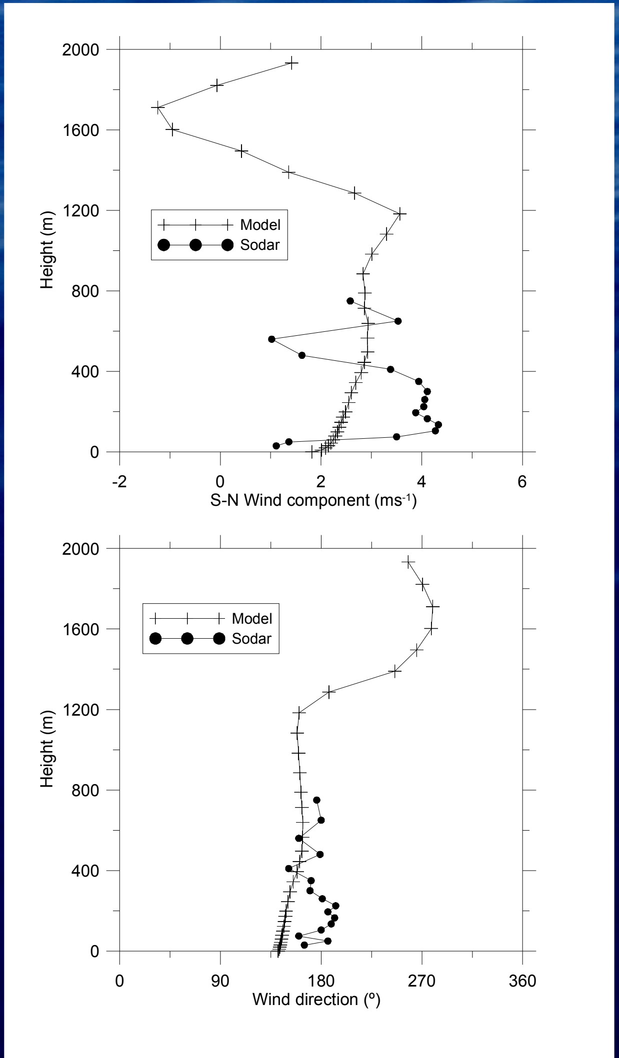


At 0300 UTC wind is leaded by the complex topography of the studied area. During day time, such as at 1000 UTC, sea breeze begins to develop firstly near the coast indicating the sea breeze onset, while later, at 1600 UTC, the sea breeze propagates further inland up to a distance of about 70 km. From this point, it is blocked up by the complex topography.

THE IMPACT OF THE SEA-BREEZE ON THE VERTICAL STRUCTURE OF THE LOWER ATMOSPHRE (ABL)

- We use the Sodar Doppler (monitor wind profiles).

- The output analysis of the MM5 mesoscale model.



In this figure you can see the comparison between wind profiles measured by Doppler Sodar and modelled with MM5

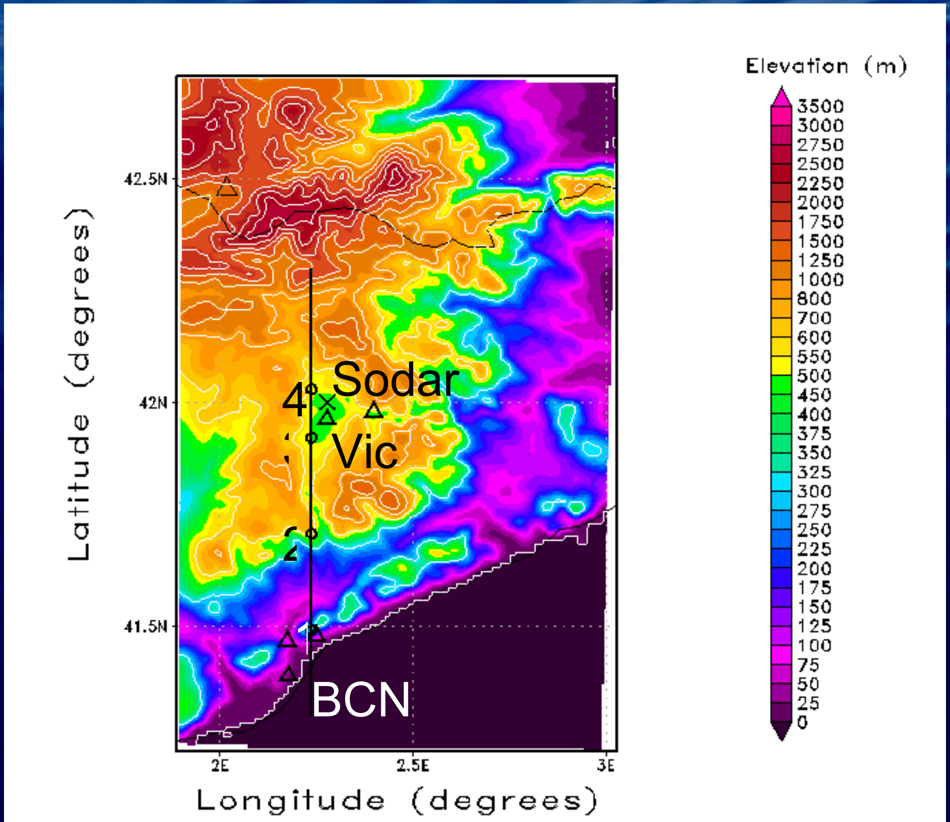
Results show quite good agreement for wind direction, although the model tends to underestimate the S-N component.

For this period, the Sodar Doppler vertical range is to low to detect the sea-breeze return.

Concerning to the MM5 model output:

The analysis is mainly made through a cross section in the south north direction, in particular we used the vertical profiles corresponding to vertical columns passing through the points 1, 2, 3, and 4.

Through this cross section, we try to understand the sea-breeze circulation and its components:

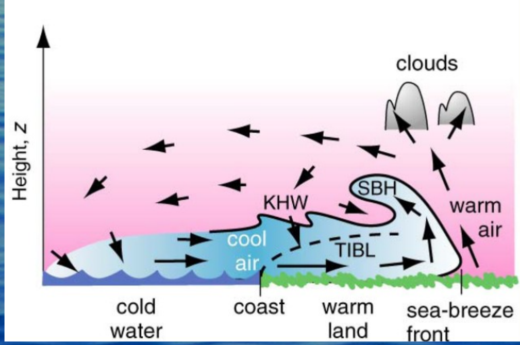


- The sea-breeze front.
- The evolution of the thermal internal boundary layer
- The development of Kelvin- Helmoltz billows.

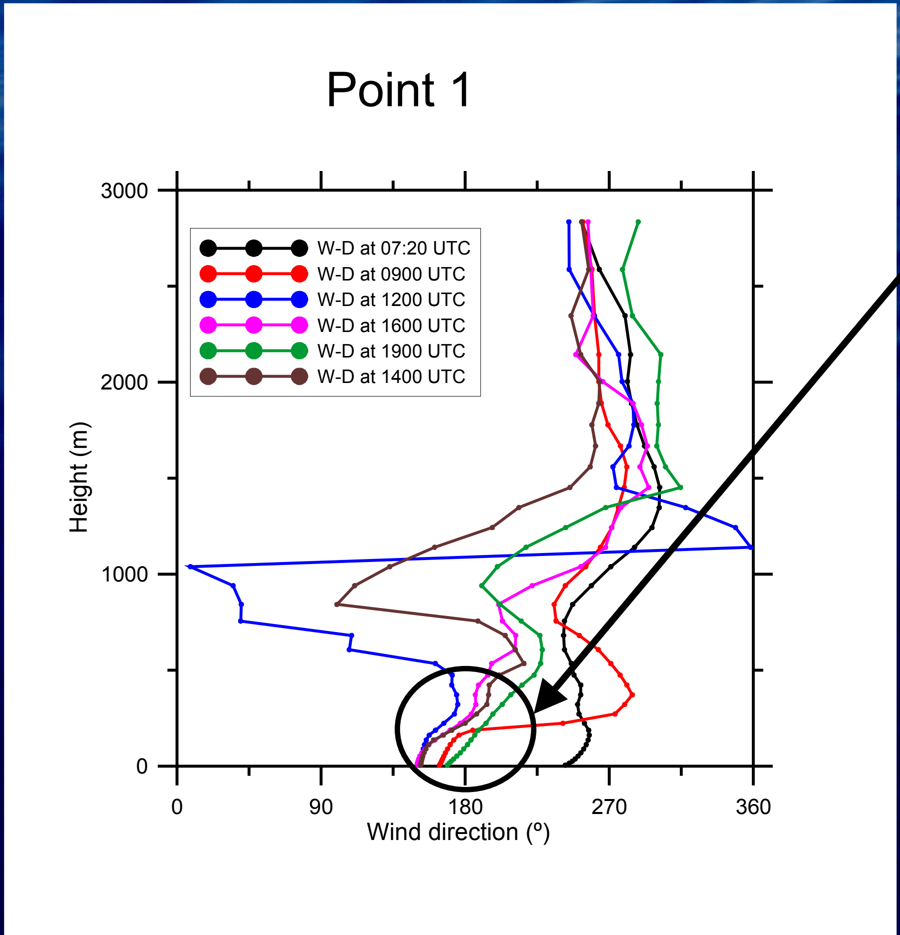
Sea breeze front (landward edge of the sea breeze flow)

Characterized by:

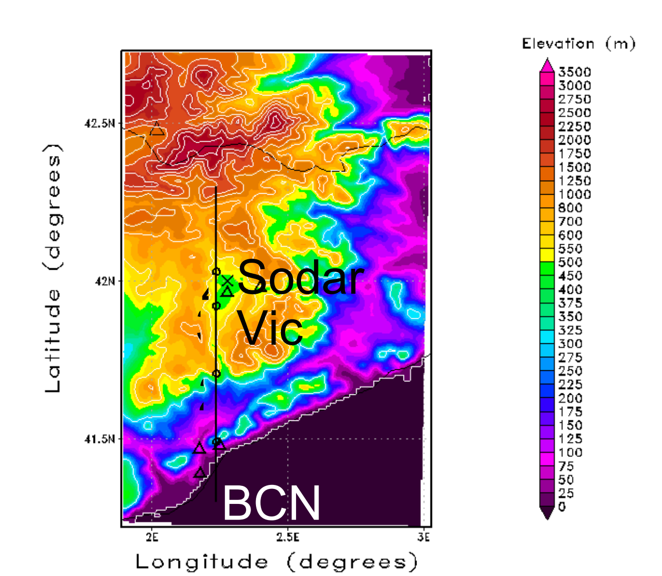
- Sudden variation of W-V; W-D; T; q;

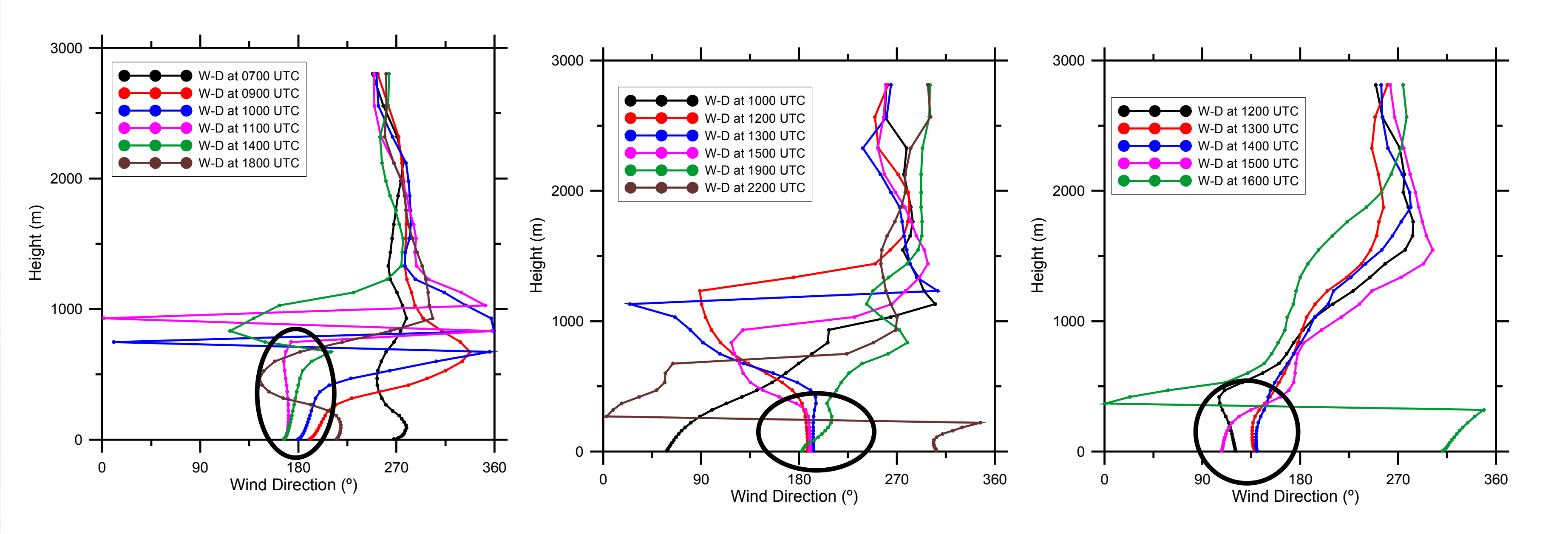


In this study, we use the simulated vertical profile of wind direction at points 1,2,3 and 4 to analyze the sea breeze onset and development.



At point 1, the sea- breeze onset is at 08:00 UTC. From this time up to 1900 UTC is well developed prevailing up to 2000 UTC . After this time wind velocity decreases (below 1 ms-1)





At point 2:
- Sea-breeze onset is at 0900 UTC.
- It is completely developed from 1000 to 16 UTC decays later and ends at 2000 UTC

At point 3:
Sea-breeze onset is near 1200 UTC
It is completely developed from 1200 UTC to 1500 UTC, decays later and ends at 2000 UTC.

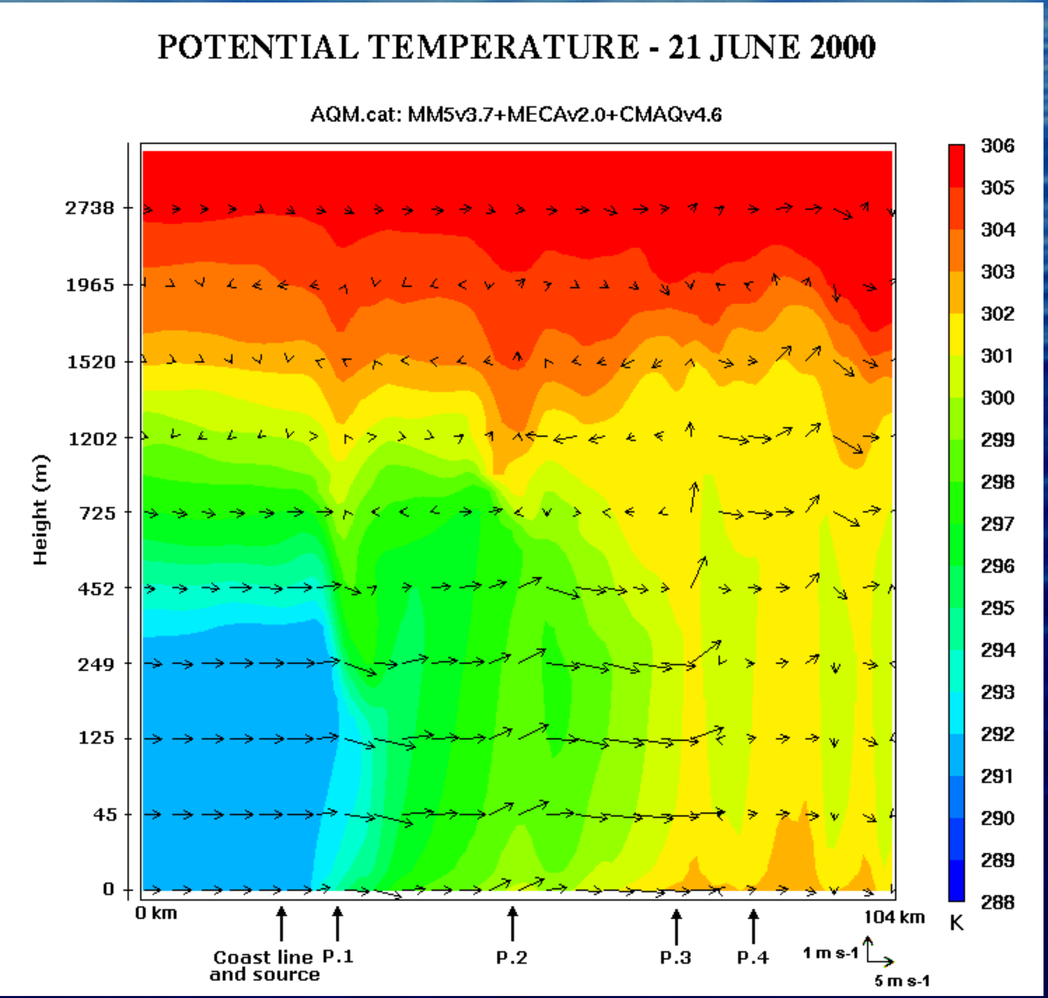
At point 4:
Sea-breeze onset is near 1300 UTC
It is completely developed from 1300 to 1400 UTC, decays later and ends at 1600 UTC.

The sea-breeze vertical extent is maximum at point 2.

Its intensity is maximum at points 2 and 3 with values between 6 and 7 ms^{-1}. This maximum, is located between 100 and 150 m.

Related to the time duration, the maximum is at point 1 (12 h), and the minimum at point 4 (3 h).

Going on with the sea breeze front and looking at this figure



Potential temperature isotherms and wind vectors over the cross section at 1400 UTC

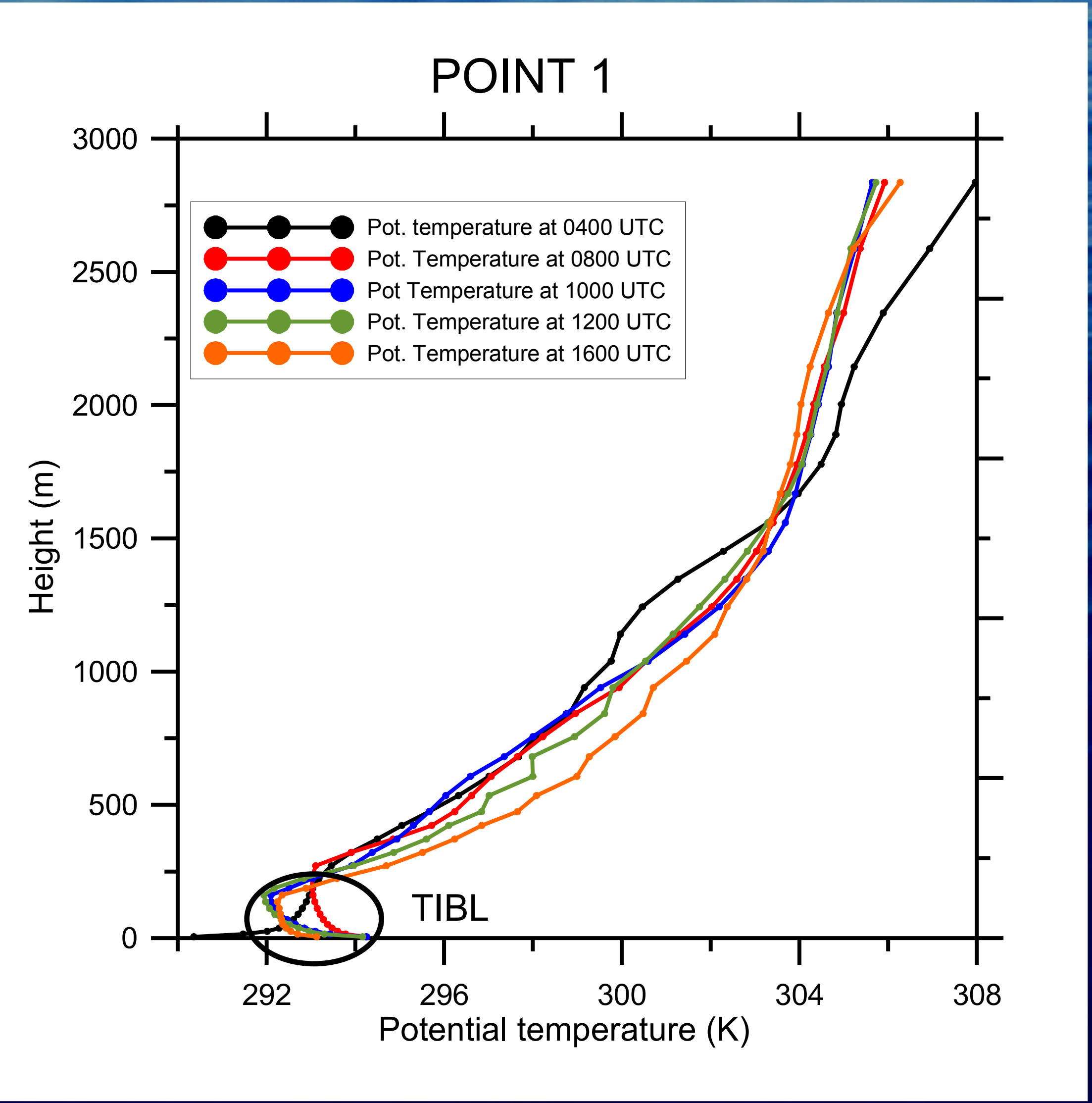
We observe two main characteristics:

The formation of the lobe, which is due to convective instability caused by the head riding over less dense fluid (Simpson et al., 1977).

•Updrafts within continental and marine air masses in the vicinity of the sea front.

•All this ABL alteration leads to the formation of a TIBL, which vertical growth depends on the convective and mechanical turbulence (Batcharova et al., 1999).

To go deeper on the TIBL, modelled vertical profiles of potential temperature (VPPT) are analyzed along the cross section:

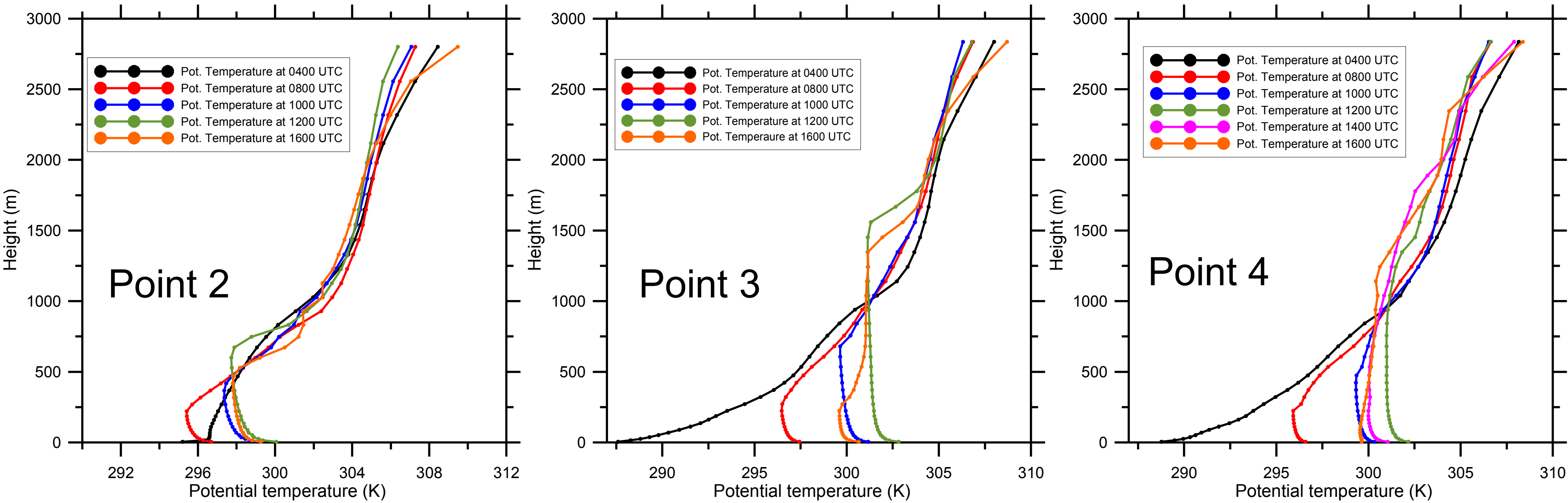


At point 1 the VPPT indicate the formation of a TIBL, which vertical extent is about 250 m.

Perhaps too low, as MY scheme tends to underestimate, mixing layer depth (Srinivas, et al., 2007), but this scheme is the only one that provides turbulent kinetic energy (TKE) as a prognostic variable.

When TIBL forms, it limits the vertical pollutants spread, leading to the fumigation phenomena, as we will see in next section.

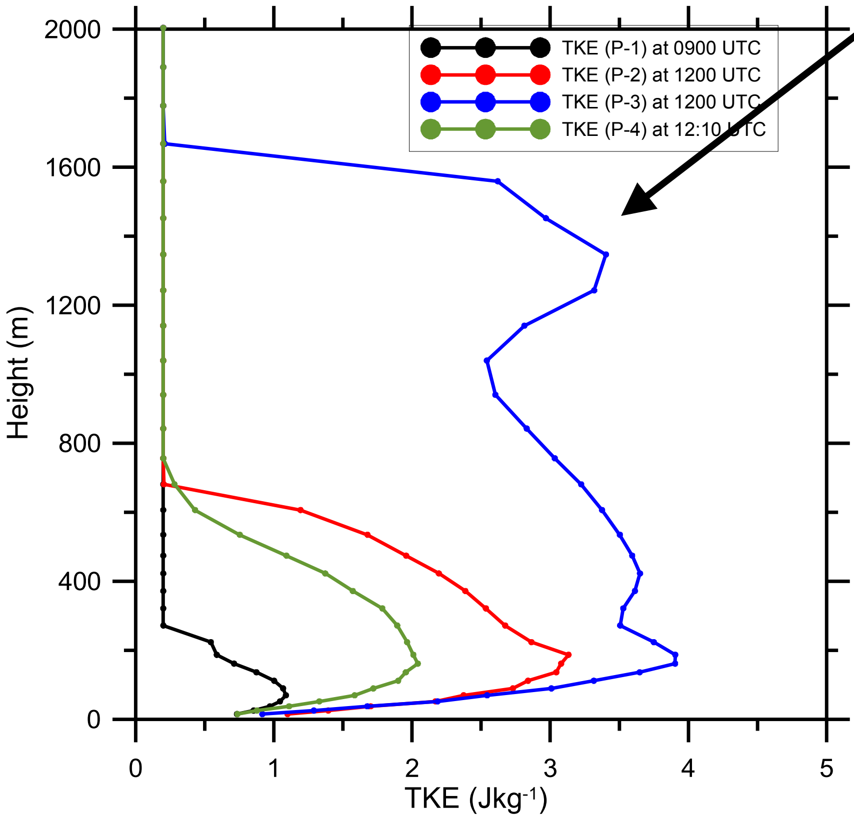
How the TIBL increases with inland distance, which gradually merges with the generic inland boundary layer.



The maxima vertical extents are:

- Near 600 m at point 2.
- Around 1600 m in point 3.
- Around 750 m in point 4

In addition, TKE vertical profiles also give a measure of the coastal and inland ABL vertical extent (height where TKE vanishes).
The reason for this constant value is because in ETA scheme, the TKE minimum value is set to 0.2 $m^2\ s^{-2}$ in weak turbulence conditions, in order to prevent run away cooling (Soler et al., 2007).

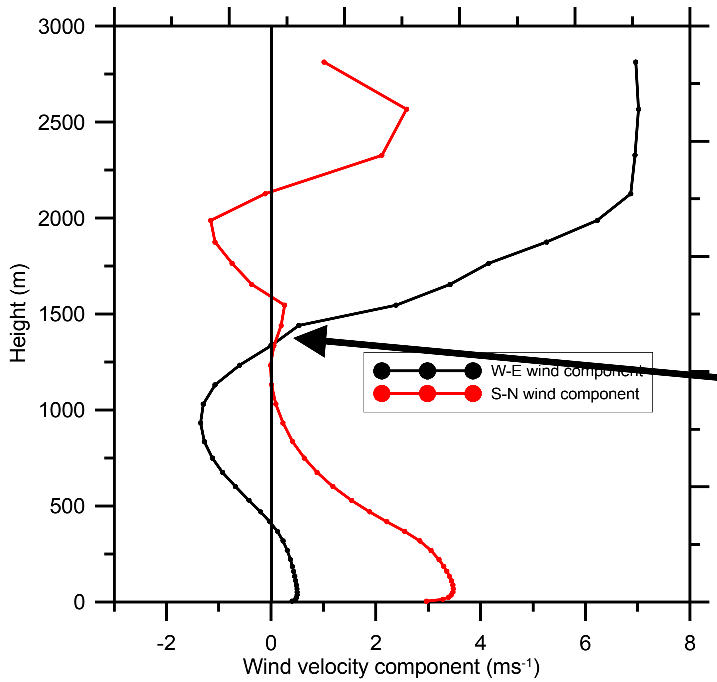


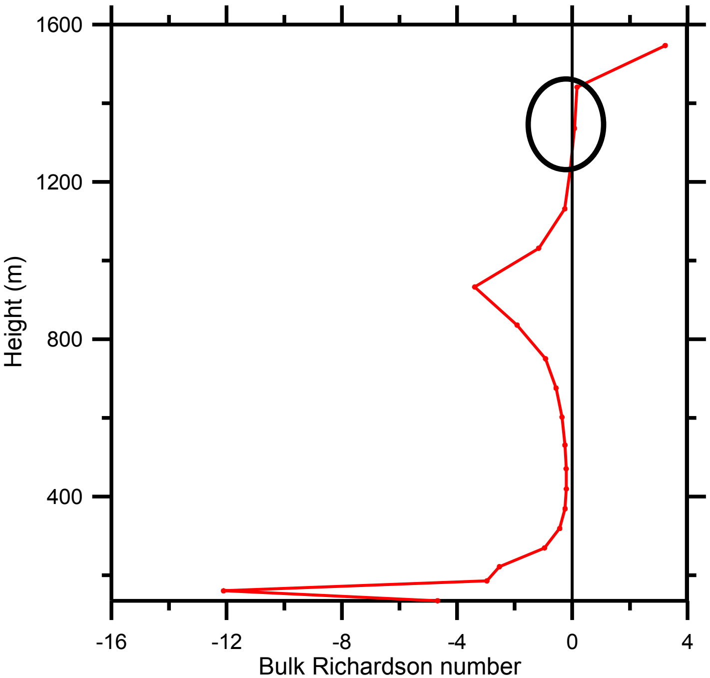
It is important to remark the TKE second peak value appearing at point 3 at 1200 UTC.

Under strong shear between
sea-breeze
→
←
return flow
and limited static stability (R_i < 0.25)

Kelvin Helmholtz billows (K-H) can develops close to the head region.

The billows grow, reach maturity and eventually breaks, generating turbulence.





- In addition, when KHB breaks propagates backward away from the front and are centred along the zero-velocity boundary (the line along which the horizontal velocity component of the sea breeze equals zero, Sha et al., 1991)

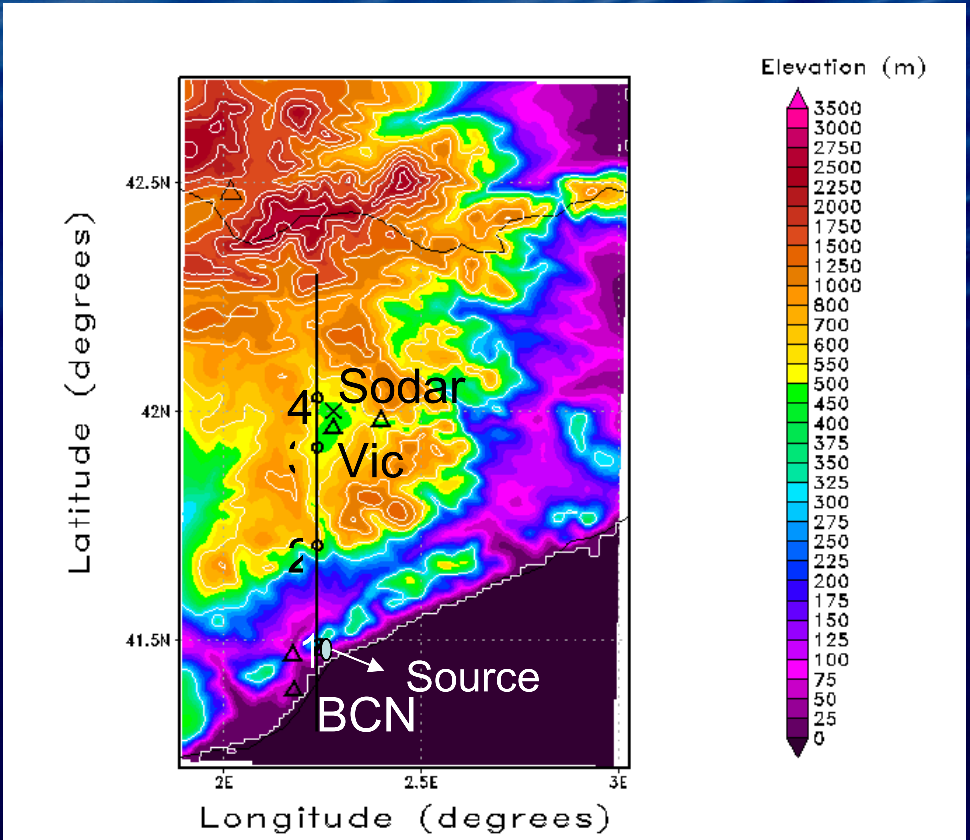
- In the same way, vertical profiles of Bulk Richardson number shows at the same layer a value lower than the critical one, 0.25. It suggest that the conditions could be favourable for K-H billows to be formed and breaks.

DISTRIBUTION OF POLLUTANTS UNDER SEA-BREEZE CONDITIONS

•We have considered ozone and PM10.

•Models: MM5 coupled to CMAQ model.

•To study the 3D distributions we have only considered a virtual source located at ground level in one of the industrial areas of Barcelona. Although it is a virtual source, their emission rate is close to the real emissions of this area.



Pollutants were emitted continuously with the following rates:

• NO_2 (192 gs^{-1})

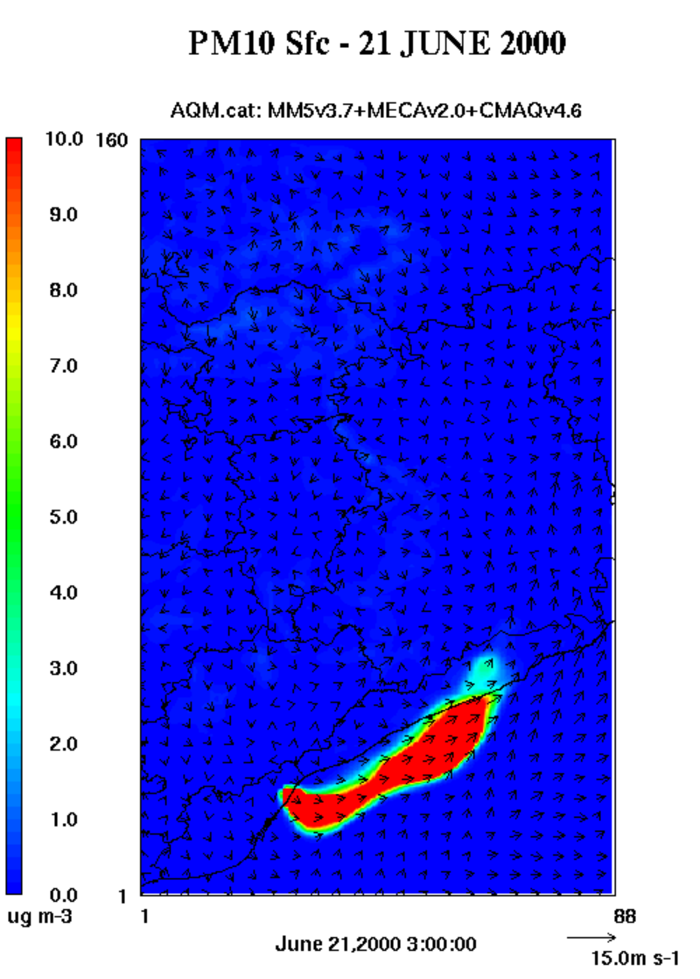
•VOC's (39.5 gs^{-1})

•PM10 (72 gs^{-1})

The 3D distribution is studied analyzing at different time intervals

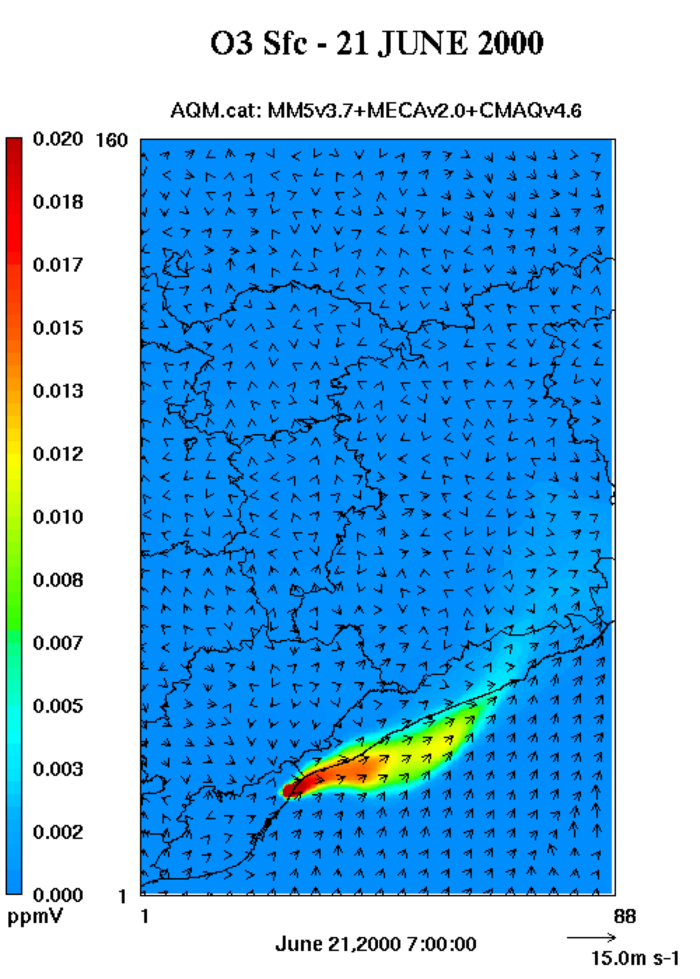
The pollutant concentration → In a horizontal cross sections at different heights → In the vertical cross section previously described.

PM10 and ozone

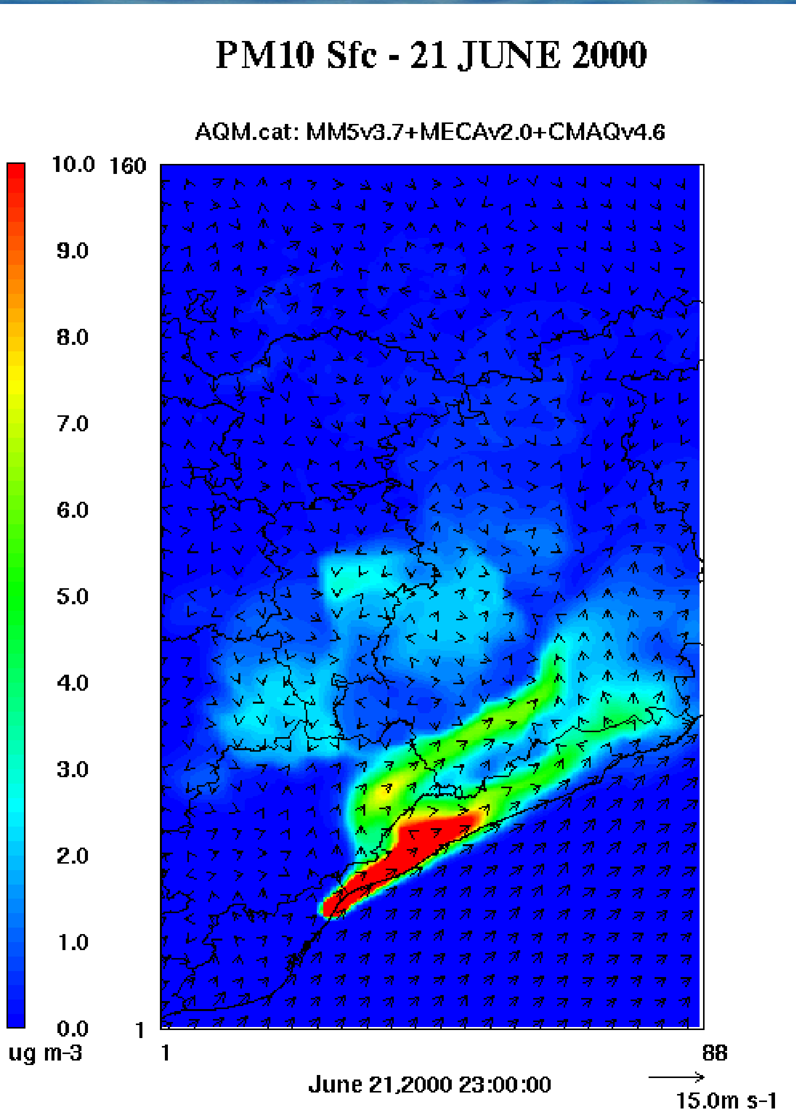


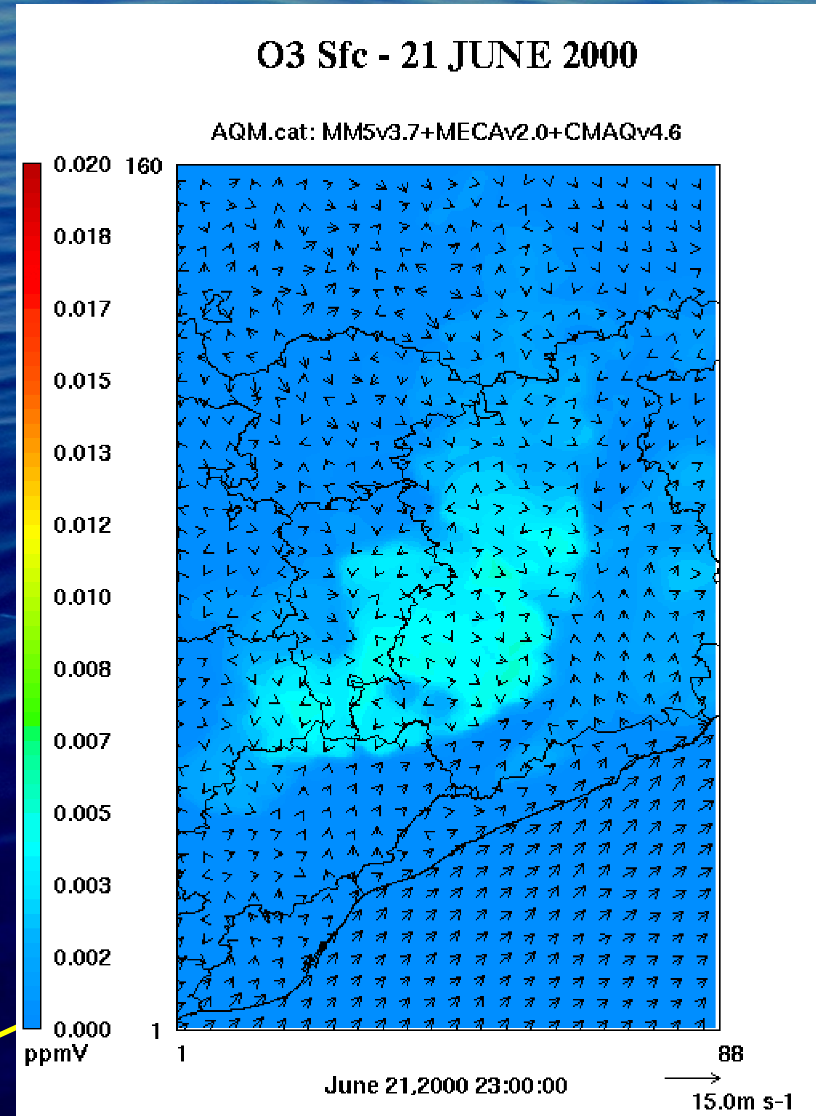
Ground level concentrations in a horizontal section.

At 0700 UTC maximum concentration is located over the sea parallel to the coast as at this time the horizontal wind comes from the W-SW sector.



The tra[illegible]eze h.extent.

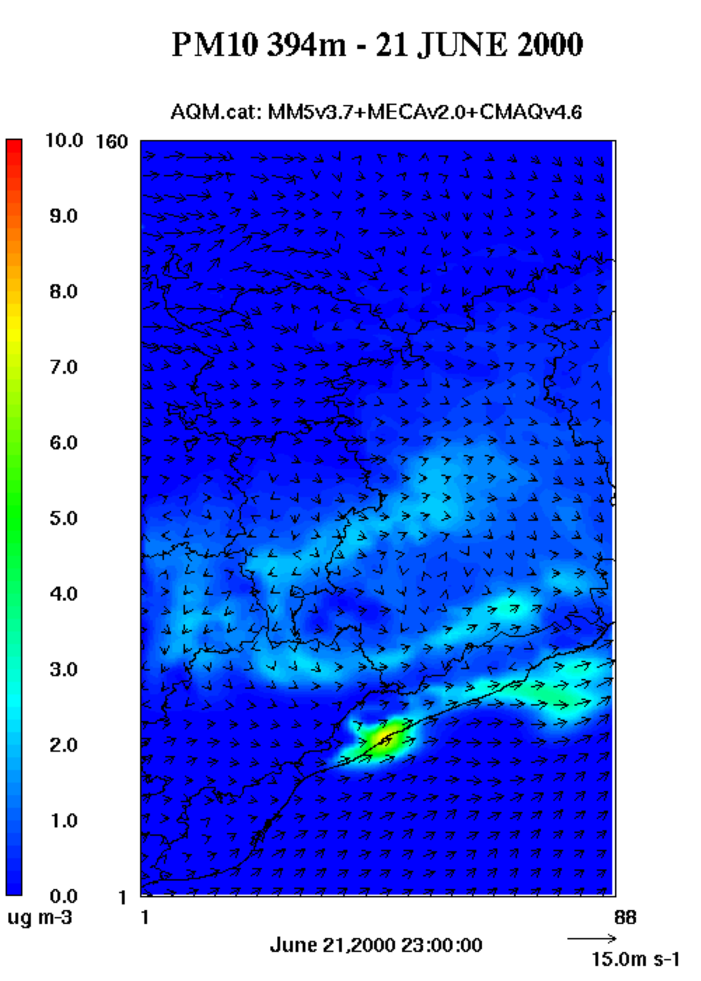


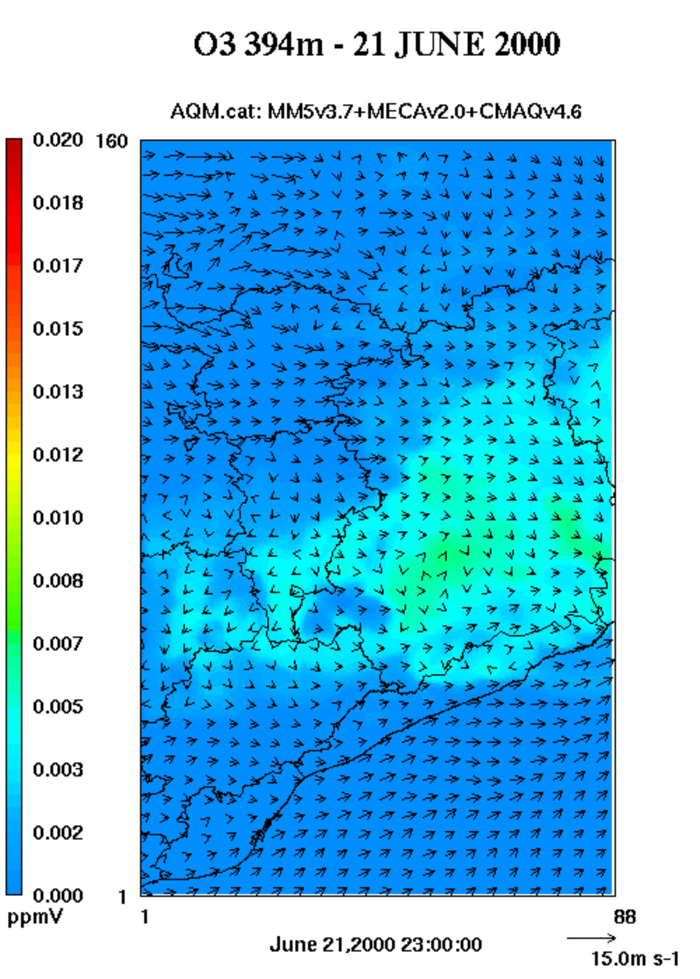


Second maxi[illegible]e and early morning respectively. Next pictures illustrate how pollutant dispersion develops with time.

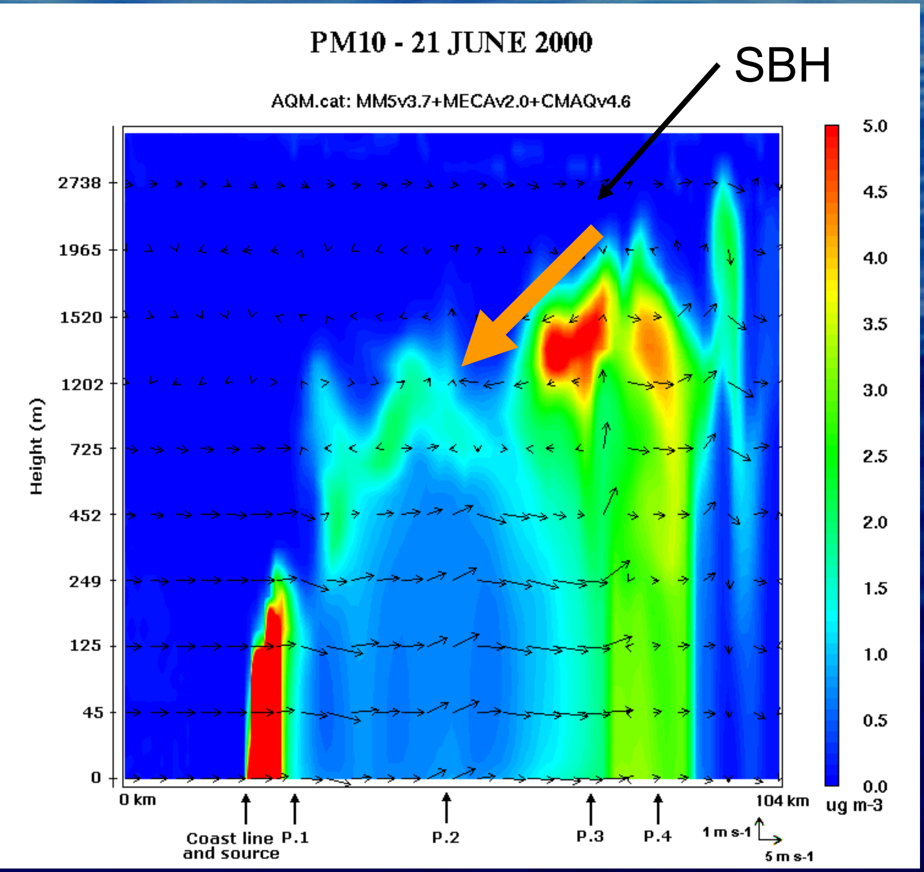
PM10 and ozone concentrations in a 400 m height horizontal cross section at 1100 UTC

- Clear example of fumigation event (PM10 and ozone) are trapped inside the TIBL near the coast.
- Next pictures show how the gravity current carries PM10 and ozone inland up to 1600 UTC, later synoptic and topographic winds will transport these pollutants to the coast.





Pollutant distribution through the vertical cross section shows:



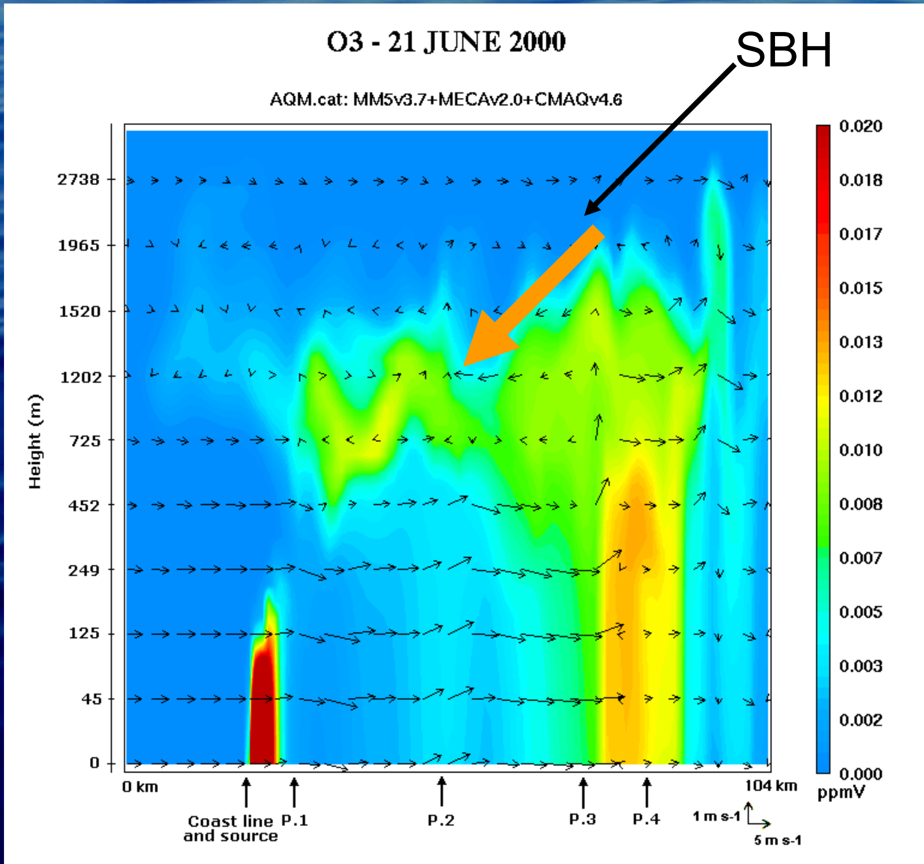


Illustration of PM10 and ozone concentrations in the vertical cross section at 1400 UTC

How PM10 and ozone are transported in altitude by the sea-breeze front, they are distributed seaward by the sea-breeze head located in altitude and behind the sea-breeze front.

CONCLUSIONS

1.- The ABL structure during a sea-breeze event has been analyzed using ground based measurements, Doppler Sodar observations and mainly numerical simulations.

2.- MM5 model has been able to reproduce the sea-breeze structure and dynamics as:
•The passage of the sea-breeze front.
•The TIBL formation increasing its height with inland distance and merging with the generic inland boundary layer.
•The possibility of KHB development inside the sea breeze system.

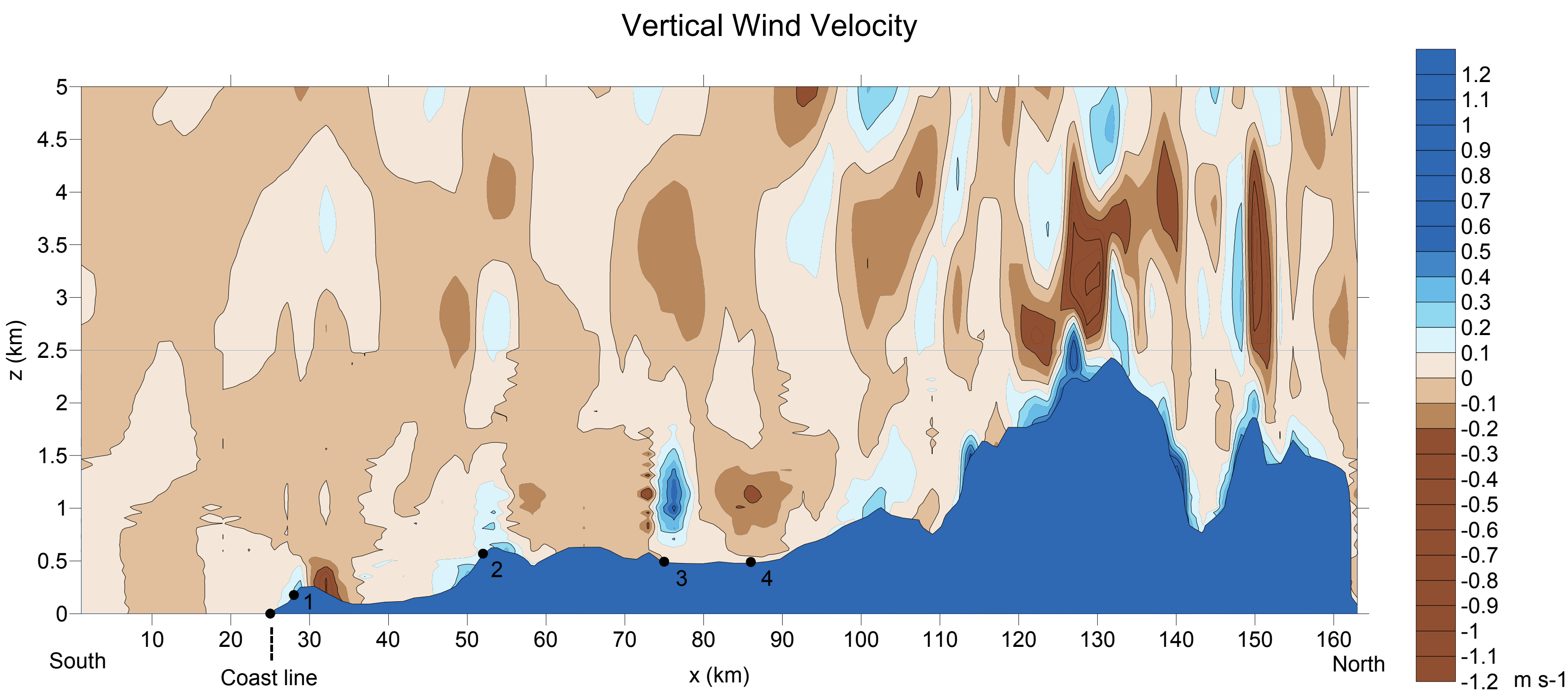
•3.- Results obtained coupling MM5 to CMAQ model show:
• The fumigation phenomenon near the coast, ozone and PM10 are trapped within the TIBL.
• The sea breeze transporting ozone and PM10 inland up to a distance of 70 km. At this point, horizontal dispersion is blocked up by the complex topography.
• Ozone and PM10 are transported in altitude by the sea-breeze front and distributed seaward by the head wind leading an elevated pollutants reservoir, which could be incorporated to the next sea-breeze system.

FINAL MAIN CONCLUSION

For air quality forecast and pollutants monitoring within highly industrialized and dense urban coastal areas, it is a requirement to go deep in the sea-breeze circulation knowledge.

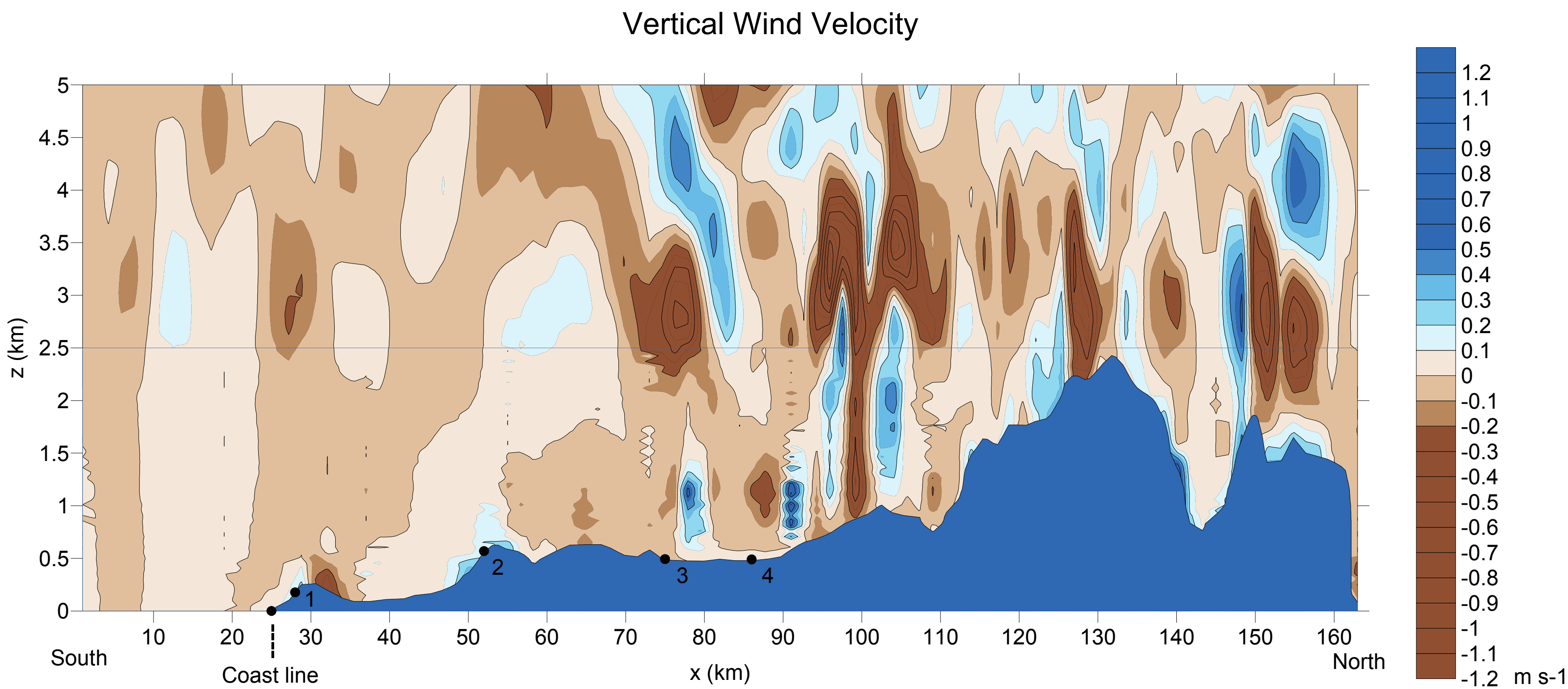
In this context, this project shows that high resolution simulations can be useful to accomplish that goal.

At 1100 UTC



Vertical Wind Velocity
z (km)
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160
South
Coast line
x (km)
North
1
2
3
4
1.2 1.1 1 0.9 0.8 0.7 0.6 0.5 0.4 0.3 0.2 0.1 0 -0.1 -0.2 -0.3 -0.4 -0.5 -0.6 -0.7 -0.8 -0.9 -1 -1.1 -1.2
m s-1

At 1400 UTC



Vertical Wind Velocity
z (km)
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
South
Coast line
x (km)
North
1
2
3
4
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
-0.8
-0.9
-1
-1.1
-1.2
m s-1