# Dynamical analysis of sea-breeze hodograph rotation in Sardinia

**N. Moisseeva and D. G. Steyn**

## Author's Response

*Reviewer comments are shown in blue. Corresponding author responses are provided in black. Changes to manuscript are highlighted in *italics.*

### Response for Reviewer 1

This paper is well-written, concise, and presents novel research with respect to sea breeze dynamics in the presence of complex topography and coastline. I think the paper is worth of publication as is, but would benefit from expanded discussion and analysis regarding the modeled hodograph rotation. These changes could be either a major or minor revision depending on how rigorous the response.

**Response:** We would like to thank the reviewer for the constructive feedback and helpful suggestions. Please see our additions and comments below.

1). The discussion of why the modeled and observed hodographs change as a function of location around the island would benefit from more discussion and background in general. For example, do inland penetration speeds and intensity of the breeze vary as a function of topography or land use types and subsequent sensible heat fluxes (which might modulate the rotation rates/types), do the breezes on either side of the island ever converge in the middle of the island, and what is the prevailing large-scale flow (if any) and how might that play into the picture? If weak large-scale flow were to be changed, would that change the rotation or have little effect?

**Response:** Thank you for highlighting the lack of background on synoptic conditions in the paper. The issue has been raised by a number of reviewers, and we agree strongly that the article does not provide sufficient clarity about possible large-scale flow. We have considered including a sample synoptic map as supplementary material for reference, but felt it was rather trivial.
Rather, we would like to include the following clarification in the revised version of the manuscript:
*The analysis is based on seven sea breeze episodes, studied previously by Furberg (2000). These pre-selected days were identified using a fairly conservative filter, ensuring the exclusion of cases with strong overriding synoptic scale winds. The model, similarly, produces very weak synoptic flow, and as evident from Fig 5. and Fig. 7, very weak synoptic rotational forcing. Hence, it does not appear to be an important factor in determining the rotation of the sea breeze.*

Regarding the remaining suggestions about the characteristics of sea-breezes in Sardinia, and their dependence on various geophysical variables:
The authors agree that all these are valid and interesting topics, but they have largely been covered in an earlier modeling study by Melas (2000). We, hence, wanted to avoid the unnecessary overlap, and focus solely on hodograph rotation, rather than general behavior of sea breezes in Sardinia.

2) Do slope flows combine with the sea breezes, and are they distinguishable from the sea breeze (I don't think they are, but these flows should be mentioned). In addition to the blocking or whatever other effects the mountains have, the mountains generate their own flows as a function of slope, vegetation type, height, etc.

**Response:**
Sardinia's complex topography certainly favors the formation of slope flows and they are generally impossible to distinguish from the SB. The two mechanisms tend to operate in combination over all of the island, particularly on the East side. However, as suggested by Melas (2000), slope winds tend to prevail near the mountains. To isolate the rotational effects of SB we, hence, performed our analysis on areas away from the coast, to avoid the local effects of slope flows, variable friction effects of land cover/use and other influences of local geophysical variables.

3). Is the synoptic forcing really 'synoptic' when it is apparently highly influenced by the breeze return circulation itself? I think this should be mentioned even if the forcing is still discussed as synoptic.

**Response:**
We agree that a more detailed description of the physical meaning of each term is needed. The revised version of the manuscript will contain a brief overview of each individual forcing term and its possible influence on sea-breeze rotation, as shown below. More specifically, the 'synoptic' term is really an upper level pressure gradient term. Unfortunately, the formulation of WRF does not allow for a separation between pressure gradient and synoptic forcing. Hence, it had to be inferred indirectly by establishing a reasonable synoptic level (850mb) to be representative of the overlaying conditions.

***Surface Pressure Gradient***
*The surface pressure gradient is predominantly driven by the temperature contrast between land and water, and its influence on the sense of rotation depends largely on the location and shape of the landmass. More subtle, local effects of the sea surface temperature inhomogeneity may further alter the turning direction of the surface wind. Moreover, non-uniform surface heating due to topography and irregular coastline of Sardinia are likely to introduce further complexity into surface pressure distribution, as previously suggested by Kusuda and Alpert (1983).*

***Synoptic Pressure Gradient***
*As the synoptic pressure gradient term is derived from total pressure gradient it inevitably represents a total of upper level forcings and true synoptic flow. While the synoptic component of the pressure gradient force generally acts in opposition to the surface gradient under SB conditions due to the formation of the SB return flow (Miller et al.,2003), it also responds to the local topography. Cyclonic and anti-cyclonic rotation may be induced depending on the direction of the local wind and shape of the topography. As SBs are known to develop on all coasts of Sardinia and have variable inland penetration the direction of dominant wind flowing over the primary mountain range on the island is likely to vary throughout the day.*

***Advection***
*Advection of the horizontal momentum may similarly result in the formation of both CR and ACR. The importance of the term depends largely on the presence of velocity gradients at a given location. Since the regions selected for our analysis are located away from the coast, we can expect the rotational effects of the advection to be of secondary importance.*

***Horizontal and Vertical Diffusion***
*The horizontal and vertical diffusion are friction driven effects, and hence always act to oppose the local wind. Varying surface roughness due to the spatial distribution of land use, cover and topography may introduce shear and rotation into wind flow. As our analysis is performed for locations away from the coast, these remain largely negligible.*

4). What does the advection term physically represent and why does it change between locations?

**Response:**
See response to Comment (3).

5). In Fig. 4 and 5, would presenting the analysis at a couple more locations around the island provide additional insight?

**Response:**
We understand that it may appear unclear why the specific locations were selected for further analysis. Whereas we are unsure that the following information is easily presentable in the revised manuscript, we would like to include it here as supplementary material (please view SupplementaryAnimation.pdf using Adobe Acrobat Reader). Fig. 4 and Fig. 6 present daytime temporal averages of rotational forcings, however, as seen in the attached animation the spatial distribution of these patterns is not stationary through the day. The animation shows the temporal evolution of total rotational forcing and its diurnal movement, as likely explained by the location of the sun relative to Sardinia. As seen in the animation, many regions around the island undergo a switch between being CR and ACR. Performing

dynamical analysis on such regions would introduce large uncertainties, and not allow us to draw any firm conclusions.
We, therefore, selected those particular locations, which maintained their sense of rotation throughout the day, and hence corresponded to largest positive and negative values of average diurnal rotational forcing. This was not explicitly stated in our paper and, hence, we'll add the following clarification in the revised manuscript:
*These locations correspond to largest positive and negative values of average diurnal rotational forcing, as they maintain their sense of rotation throughout the length of the day.*

6). A brief mention of latitude dependence if any was found (I doubt given how small the island is) and reference to this paper's findings (and comparison to these findings) would be valuable P. Alpert, M. Kusuda, and N. Abe, 1984: Anticlockwise Rotation, Eccentricity and Tilt Angle of the Wind Hodograph. Part II: An Observational Study. J. Atmos. Sci., 41, 3568–3583. doi: http://dx.doi.org/10.1175/1520-0469(1984)041<3568:AREATA>2.0.CO;2

**Response:**
As suggested, the island is too small and no latitude dependence was found.

7). No discussion of the SB hodographs as a function of distance inland from the coast were given. That would possibly be a topic of interest. The observations might not be there, but choosing a station from WRF model inland say 10 km from coast and seeing if there was any change from the coastal location could be of interest.

**Response:**
As noted in response for Comment (5), the locations for dynamical analysis were not selected arbitrarily. By focusing on off-coast locations we aimed to reduce the uncertainty due to temporal averaging of tendency values. Moreover, this allowed us to avoid the local influences of particular land features and study SB as a true mesoscale phenomenon. We have examined the evolution of rotational tendencies for a number of inland locations and while they generally resembled those presented in the manuscript large error bars did not allow us to firm conclusions.

**References:**


Kusuda, M., and P. Alpert (1983), Anti-clockwise rotation of the wind hodograph. Part I: Theoretica study, Journal of the Atmospheric Sciences , 40 (2), 487–499.

Melas, D., A. Lavagnini, and A. Sempreviva (2000), An investigation of the boundary layer dynamics of Sardinia island under sea-breeze conditions, Journal of Applied Meteorology , 39 (4), 516–524.

Miller, S., B. Keim, R. Talbot, and H. Mao (2003), Sea breeze: Structure, forecasting, and impacts, Reviews of Geophysics , 41 (3).

**Response for Reviewer 3**

We would like to thank the reviewer for his feedback and suggestions. Please find the in-text responses to comments below.

The authors conducted a modeling study to understand the terms controlling the clockwise and anticlockwise rotation of seabreezes. The terrain seems to have a significant role in determining SB hodograph rotation, which may have been fairly important in determining the different patterns of SB hodograph rotation around the island. Moreover, how those 12 stations around the island are positioned relative to the synoptic circulation pattern in that case study and hence how that might've affected SB hodograph rotation is worth looking into.

**Response:**
The 12 stations around the island were used primarily for model evaluation, rather than to understand the dynamics underlying hodograph rotation. As we were predominantly interested in larger mesoscale effects the dynamical analysis was performed in regions away from the coast, which were, hence, less sensitive to local influences of topography, land use and cover.

A case in point is pages 22891 lines 9-10, where the authors stated, "The synoptic gradient acts largely in opposition to the surface gradients, likely due to the formation of SB return flow near 850mb level". Wouldn't it be easier to illustrate the synoptic circulation pattern over the island and be quantitative about it, which they did in Fig. 5, so as to be more definitive than "likely"?

**Response:**
Thank you for highlighting the lack of clarity in both: describing the synoptic conditions, as well as explaining the meaning of synoptic gradient. The issue has been raised by a number of reviewers and we agree strongly that further clarifications are needed. Please find a detailed response to the issue as well as proposed additions to the manuscript in our Comments for Reviewer 1.
Regarding the apparent ambiguity in the wording: it is generally impossible to quantitatively separate true synoptic effects from the SB return flow. As per Melas (2000), "the return flow merges with the prevailing synoptic flow and is difficult to distinguish".

BTW, what did the authors mean by "surface gradient"? If they were referring surface pressure gradient, they should stick to the term. The presentation of their analysis can be more quantitative than it is.

**Response:**
Thank you for pointing out inconsistencies in the use of the term throughout the paper. We will revise this in the next version of the manuscript. Similarly to the

previous comment, please find the proposed additions with term descriptions in Comments for Reviewer 1.

Another comment is it is not clear why the authors conducted the idealized case study. The island has three mountain ranges. In the idealized case, they reduced it to one among a few other assumptions. If they aimed to narrow down the causes for those CR and ACR patterns by comparing the idealized with the real case, it seems to be pretty difficult, as there were a few other factors that were also different.

**Response:**
The primary reason for performing an idealized study is to attempt to generalize the findings and extrapolate them to islands other than Sardinia. On this matter, we tend to agree with Short Comments by Reviewer 2, that an idealized experiment is of interest as it allows to experiment with alternative geophysical settings. The use of idealized topography in mesoscale modelling has a substantial history, and many precedents (for example, Gaberšek and Durran, 2006 and Pathirana et al 2003). In such studies, the idealized topography allows one to draw conclusions not specific to a particular instance of a phenomenon, but to similar phenomena in general. The approach also allows conclusions about processes independent of small-scale variability in topography, coastline, roughness length and surface energy budgets.

Page 22894 lines 2-3: the authors stated, "Regions of CR and ACR are arranged on opposite coasts to that of the real Sardinia, and similarly to Corsica from the real simulation and the Attic Peninsula from Steyn and Kallos (1992)." Again, wouldn't it be helpful to show the synoptic system for that day? It seems to work in opposite directions on the west and east coast SBs. Comparing this result with Steryn and Kallos (1992) is not really that meaningful, unless they had also pointed out the terrain there was similar to the idealized terrain in this study and the synoptic flow was quite the same etc.

**Response:**
Thank you for pointing out the disconnection in the argument. Attic Peninsula does, in fact, carry more topographic similarities with the idealized simulation than Sardinia. It is dominated by a single mountain range with similar elevation to that of our idealized island. Similarly to our results, the synoptic flow in Steyn and Kallos (1992) was also found to be of little importance in the Attic Peninsula, simply due to the nature of conditions typically associated with sea-breeze days. To summarize, we will include the following clarification following the quoted sentence in the revised manuscript:
*This can likely be attributed to similarities in the shape and elevation of topography of the Attic Peninsula to that of the idealized simulation.*

On the same page, lines 12 -14: "This may be an indication of a model response to the morning switch in the direction of surface heat flux, which in some cases produces a spike in model fields." Again, this can easily be quantitative by showing

the diurnal cycle of modeled surface heat flux to back up this point, instead of leaving it qualitative and speculative.
Overall, this paper can use some revision to make their analysis more quantitative and detailed.

**Response:**
While we have certainly verified that the timing of the switch in the direction of surface heat flux does in fact coincide with the occurrence of the spike in model fields (in exactly the way suggested by the reviewer), we are wary of drawing such firm conclusions. Though the events occur simultaneous, the complexity of interactions between land, surface and boundary routines in the WRF model makes the relationship difficult to quantify further.

**References**


Gaberšek, Saša, and Dale R. Durran. "Gap flows through idealized topography. Part II: Effects of rotation and surface friction." *Journal of the atmospheric sciences* 63.11 (2006): 2720-2739.

Pathirana, Assela, Masafumi Yamaguchi, and Tadashi Yamada. "Idealized simulation of airflow over a mountain ridge using a mesoscale atmospheric model." *Annual Journal of Hydraulic Engineering, JSCE* 47 (2003): 31-36.

Melas, D., Lavagnini, A., and Sempreviva, A.: An Investigation of the Boundary Layer Dynamics of Sardinia Island under Sea- Breeze Conditions, J. Appl. Meteorol., 39, 516–524, 2000.

Steyn, D. and Kallos, G.: A study of the dynamics of hodograph rotation in the sea breezes of Attica, Greece, Bound-Lay. Meteo- rol., 58, 215–228, 1992.

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# Dynamical analysis of sea-breeze hodograph rotation in Sardinia

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**Abstract.** This study investigates the diurnal evolution of sea-breeze rotation over an island in the mid-latitudes. Earlier research on sea-breezes in Sardinia shows that the onshore winds around various coasts of the island exhibit both the theoretically predicted clockwise rotation as well as seemingly anomalous anti-clockwise rotation. A non-hydrostatic fully compressible numerical model (WRF) is used to simulate wind fields on and around the island on previously-studied sea-breeze days and is shown to accurately capture the circulation on all coasts. Diurnal rotation of wind is examined and patterns of clockwise and anti-clockwise rotation are identified. A dynamical analysis is performed by extracting individual forcing terms from the horizontal momentum equations. Analysis of several regions around the island shows that the direction of rotation is a result of a complex interaction between near-surface and synoptic pressure gradient, Coriolis and advection forcings. An idealized simulation is performed over an artificial island with dramatically simplified topography, yet similar dimensions and latitude to Sardinia. Dynamical analysis of the idealized case reveals a rather different pattern of hodograph rotation to the real Sardinia, yet similar underlying dynamics. The research provides new insights into the dynamics underlying sea-breeze hodograph rotation, especially in coastal zones with complex topography and/or coastline.

## 1 Introduction

Sea-breeze (SB) circulation is a mesoscale phenomenon driven by a mesoscale, horizontal pressure gradient resulting from the differential heating of land and water. Recently, with the availability of fully compressible three-dimensional non-hydrostatic numerical models there has been a tremendous improvement in our understanding of the complex nature of SB and the associated non-linear interactions on several scales, from meso-$\beta$ to micro-scale (Miller et al., 2003). Due to this complexity, numerical models present the only tool for studying the dynamics of SB circulation over real domains with complex topography. As shown by Zhang (2005), Ramis and Romero (1995), Steyn and Kallos (1992), Mahrer and Segal (1985) and Walsh (1974) the general structure and diurnal cycle of the SB circulation can be well reproduced by a numerical model and agrees closely with the aspects developed by theoretical studies and observations.

Crosman and Horel (2010) conducted a thorough review of existing literature on numerical studies of SBs to summarize the current state of knowledge of the dependence of SB on geophysical variables. Despite the large numbers of scientific studies devoted to the subject, Crosman and Horel have identified several gaps in understanding of SB circulation. Among them is the ambiguity associated with SB dependence on topography and anti-clockwise hodograph rotation.

The mechanism behind the SB rotation was first explained by Haurwitz (1947), as an effect of the Coriolis force. One can therefore expect all SBs in the Northern hemisphere and their corresponding hodographs to rotate clockwise. However, a number of cases have been identified where an apparently anomalous anti-clockwise hodograph rotation (ACR) was observed. Neumann (1977) showed, using a two-dimensional sea and land-breeze model, that the rate of turning of the direction of sea and land-breezes is far from uniform over the diurnal cycle. Simpson (1996) expanded on the analysis proposed by Neumann and concluded that in general the Coriolis force, which is the primary factor driving typical clockwise hodograph rotation (CR) in the Northern Hemisphere, is not always the most important term in the equations of motion. Kusuda and Alpert (1983) considered the issue analytically and described hodographs in terms of phase shifts. Using a linear model they showed that ACR hodograph rotation can be generated by including an ACR thermal force. The switch to ACR occurs at a critical value, which is a function of friction and latitude. They also employed a simple two-dimensional model with artificial topography and found that the dominant term inducing the rotation was a combination of pressure and surface pressure gradient. In contrast to primarily analytical and idealized work, Steyn and Kallos (1992) used a three-dimensional numerical mesoscale model to study the issue in the Attic Peninsula, Greece. Their findings were in agreement with Kusuda and Alpert (1983) as well as local observations. The paper demonstrated that a balance of pressure and terrain gradient forcing is dominant, and can result in either CR or ACR. While the studies described present extremely valuable insight into the diurnal evolution of the SB, overall hodograph rotation has been largely neglected since the original study by Haurwitz (1947), according to Crosman and Horel (2010) who suggest simulating the hodograph rotation under a wide array of geophysical variables as a topic for future exploration.

Several studies have previously examined SBs in Sardinia ((Dalu and Cima, 1983; Melas et al., 2000)), which is located in the Western Mediterranean Sea and provides an ideal platform for investigation of SB dynamics in the mid-latitudes. SBs are known to be fairly frequent in the Mediterranean region and rich meteorological datasets are readily available from fifty meteorological stations on the island, of which twelve coastal locations are shown on Fig. 1. Sardinia has a complex topography with three mountain ranges situated slightly closer to the eastern side of the island. The island is approximately elliptical in shape, with length and width 270km and 140km, respectively.

A recent study by Furberg (2002) focused on developing a statistical climatology of SB in Sardinia based on data collected over approximately 16-26 months using the network of 12 coastal stations shown in Fig. 1. The paper examines diurnal hodograph rotation and also shows that under appropriate conditions SB can develop simultaneously on all coasts of Sardinia, which is in close agreement with the finding of Melas et al (2000). More importantly, the study demonstrates using averaged wind hodographs that both CR and ACR are known to occur along the coast of the island. These findings provide an extremely useful starting point for numerical modeling of the SB circulation and hodograph rotation in Sardinia.

# 2 Methods

## 2.1 Model setup

The Weather Research and Forecast Model (WRF-ARW) is used to simulate seven SB episodes during warmer months of 1997-1998 in Sardinia identified in Furberg's (2000) work. While the model offers great operational forecasting capabilities, effectively no options for dynamical analysis are available, which presents a serious limitation to those using WRF for research: while the model demonstrates excellent performance and accuracy it does not allow one to investigate the dynamics driving the modelled phenomena. In order to overcome this limitation the model code was adjusted to allow for the extraction of the individual tendency terms of the horizontal momentum equations. The details of the introduced changes, as well as modified code are available as supplementary material.

The knowledge that the episode days identified by Furberg (2000) had favorable atmospheric conditions for the formation of SB on the island provides an extremely useful starting point for the numerical simulation. Identified primarily on the basis of diurnal reversal of surface wind direction, first suggested by Steyn and Faulkner (1986) the following days were considered SB days on Sardinia:

- 17 May, 1997
- 15 August, 1997
- 20 May, 1998
- 30 May, 1998
- 20 June, 1998
- 21 June, 1998
- 29 June, 1998

Identical domain configuration was used for all of the SB episode days. The simulation was set up on a two-way nested domain centered on the island of Sardinia with 50 vertical eta-levels. The parent and nest domain grid spacing was set to 9km and 3km respectively. Selection of such horizontal spacing was largely based on earlier studies by Steyn et al. (2013), which concluded that at this resolution the subgrid-scale effects in WRF have no significant influence on the overall dynamics of the SB.

The model was initialized using Climate Forecast System Reanalysis (CFSR) high resolution pressure-level (0.5 degrees latitude/longitude) and surface and radiative flux (0.3 degree gaussian grid) 6-hour forecast data. Each of the SB days identified by Furberg (2000) was simulated over 30 hours to account for a 6 hour spin-up, beginning at 18:00 UTC of the previous day. As we are primarily interested in day-time dynamics, the analysis was performed starting 09:00 UTC, i.e. 15 hours after the beginning of each simulation. Wind and dynamical tendency fields were output six times each hour and subsequently averaged to produce an estimate of hourly values.

## 2.2 Model evaluation

The model was evaluated using the observational data available for the twelve meteorological stations operated by the Servizio Agrometeorologico Regionale per la Sardengna (SAR), who manage a network of 50 stations over the island. The primary goal was to demonstrate that the model captures the SB circulation and hodograph rotation on all coasts, and hence we focused on comparing the winds and associated diurnal evolution of wind hodographs at each of the station locations. For the purpose of the analysis, twelve individual modelled grid points were selected on the island which are closest to the location of the meteorological stations based on latitude and longitude.

The first step was to determine the direction of the onshore wind vector for both modelled and observational data. The $u$ and $v$ wind components at 10m were converted into polar coordinates and plotted as a hodograph for both observed and modelled winds. Figure 2 shows the results from a single simulated SB episode on 21 June, 1998. A range of onshore/offshore directions was tested for each data set and the onshore wind vector was defined to be the one that produced the smallest root-mean squared error (RMSE) between model and observation, and hence corresponding to the primary direction of air flow.

Note that the modelled and observed onshore directions were defined separately for the observed and modelled winds and allowed to differ for each individual day. While these directions were generally found to be in close agreement, several stations showed a considerable discrepancy between model and observations (e.g. Valledoria, Jerzu). Introduction of this flexibility is a particularly important aspect of the proposed evaluation methodology. While it may seem that this assumption makes the evaluation criteria less stringent, it in fact, acts as a filter to isolate the subgrid-scale effects that are inevitably present in observational data, and entirely absent from the model output. As the hourly winds are subsequently projected onto the identified onshore direction, a slight difference in the definition of the onshore axis due to inclusion/exclusion of the subgrid-scale effects can easily mask the model's overall good performance. The advantage of this approach is that it allows us to compare and evaluate the larger scale kinematics and their diurnal evolution, rather then the local effects due to subgrid-scale phenomena.

Overall, individual (non-averaged) daily hodographs present one of the most stringent criteria for model evaluation, as instantaneous wind data is inevitably highly variable. However, as seen in Fig. 2, there is good agreement between modelled and observed winds. While no observational record is present for Siniscola station for the modelled day, there appears to be a greater discrepancy between simulated and observed data on the eastern coast. Modelled winds at Jerzu station, located beneath the highest peak in Gennargentu Ranges (1834m) (Fig. 1), are consistently inferior to simulations at other stations on all simulation days. This can likely be explained by steep topography in close proximity to the east coast, which presents a well known challenge for numerical models. The nonorthogonal grid lines introduced due to the use of terrain-following vertical coordinate in WRF are known to produce significant truncation errors when attempting to calculate horizontal gradients, leading to computational inaccuracy of advection, diffusion and pressure gradient terms (Yamazaki and Satomura, 2010).

The simulated and observed wind fields were then projected onto the corresponding identified onshore direction for each station and compared. As seen in Fig. 3, the model evaluation demonstrates excellent agreement between model and observations, both due to exceptional model performance and successful evaluation strategy. Note that the stations where the onshore directions determined by RMSE differed considerably between model and observations still show strong agreement in the development and shape of the onshore wind component, suggesting that the overall structure of the SB at that location is well represented. WRF clearly captures the kinematics of the SB circulation, and hence can be used for further dynamical analysis of the SB structure.

## 3 Dynamical analysis of real-case simulation

### 3.1 Rotation of the horizontal wind

The horizontal momentum equations solved in WRF can be represented in simplified vector form as

$$\frac{\partial \boldsymbol{V}_h}{\partial t} = \frac{\partial \boldsymbol{V}_{pg}}{\partial t} + \frac{\partial \boldsymbol{V}_{adv}}{\partial t} + \frac{\partial \boldsymbol{V}_{cor}}{\partial t} + \frac{\partial \boldsymbol{V}_{hdif}}{\partial t} + \frac{\partial \boldsymbol{V}_{vdif}}{\partial t} \quad (1)$$

where $\boldsymbol{V}_h$ is total horizontal velocity vector, $\boldsymbol{V} = (U, V)$ and subscripts $pg$, $adv$, $cor$, $hdif$, and $vdif$ correspond to forcing due to pressure gradient, advection, Coriolis, horizontal and vertical diffusion. Taking the 850 mb pressure level to be representative of overlying synoptic weather conditions, the pressure gradient term $\boldsymbol{V}_{pg}$ can be further separated into synoptic $(syn)$ and surface $(surf)$ forcing by assuming that

$$\boldsymbol{V}_{syn} = \boldsymbol{V}_{pg}(850mb) \quad (2)$$

The remaining pressure gradient forcing is then assumed to be due to surface effects, i.e.

$$\boldsymbol{V}_{surf} = \boldsymbol{V}_{pg} - \boldsymbol{V}_{syn} \quad (3)$$

It is important to note that the formulation of WRF-ARW does not allow us to further separate the pressure gradient forcing into components to isolate the effects of topography, coastline curvature and aspect, land/sea temperature contrast, roughness and other local features.

Full horizontal momentum equations considered for dynamical analysis then become

$$\frac{\partial \boldsymbol{V}_h}{\partial t} = \frac{\partial \boldsymbol{V}_{surf}}{\partial t} + \frac{\partial \boldsymbol{V}_{syn}}{\partial t} + \frac{\partial \boldsymbol{V}_{adv}}{\partial t} + \frac{\partial \boldsymbol{V}_{cor}}{\partial t} + \frac{\partial \boldsymbol{V}_{hdif}}{\partial t} + \frac{\partial \boldsymbol{V}_{vdif}}{\partial t} \quad (4)$$

Following Neumann (1977), the tendency of horizontal wind direction can be expressed as

$$\frac{\partial \alpha}{\partial t} = \frac{1}{\boldsymbol{V}_h^2} \boldsymbol{k} \cdot (\boldsymbol{V}_h \times \frac{\partial \boldsymbol{V}_h}{\partial t}) \quad (5)$$

where $\alpha$ is the angle of local wind relative to the positive $x$-axis, $\boldsymbol{V}_h$ is the horizontal wind vector, and $\boldsymbol{k}$ is a vertical unit vector. Positive and negative values of $\frac{\partial \alpha}{\partial t}$ correspond to ACR and CR respectively. Expanding the cross product in Eq. (5) using the components of the total wind vector in Eq. (4) it is possible to compare the magnitudes of the terms contributing most strongly to the rotation.

### 3.2 Regional patterns of hodograph rotation

Using the definition of $\frac{\partial \alpha}{\partial t}$ in Eq. (5) it is possible to create contour maps of regions of CR and ACR for the simulated real domain. 20 June, 1998 was selected as a test case, as it has shown strong agreement between model and observed hodographs based on the results of model evaluation. Hourly contours produce extremely complex patterns. As we are primarily interested in identifying possible invariant features of the circulation, daytime hourly $\frac{\partial \alpha}{\partial t}$ values were averaged between 09:00 to 17:00 UTC to produce $\frac{\partial \alpha_{day}}{\partial t}$. Figure 4 shows daytime regional patterns of CR ($\frac{\partial \alpha_{day}}{\partial t} < 0$) and ACR ($\frac{\partial \alpha_{day}}{\partial t} > 0$) for the real case simulation.

The southwestern region of the nested domain is dominated by strong CR. The CR pattern continues around the northern part of Sardinia. The SB circulation on the eastern coast of the island is largely ACR. The southern tip of Sardinia shows a switch between CR and ACR likely due to the presence of the southern mountain range - the Sulcis Mountains (Fig. 1). Overall the rotation pattern appears to respond to the local features of the terrain. The island of Corsica to the north of Sardinia exhibits a very complex pattern with several extremely sharp gradients in rate of change of direction. This can likely be explained by Corsica's much steeper topography and slopes and proximity to the boundary of the nested domain.

Also identified in Fig. 4 are four subregions off the southwestern, northwestern, southeastern and southwestern coasts of the island exhibiting either CR or ACR. Each subregion is a square of 8x8 grid points covering an area of 576 km$^2$. The chosen locations correspond to largest positive and negative values of average diurnal rotational forcing, as they maintain their sense of rotation throughout the length of the day. These regions were selected for further dynamical analysis in an attempt to understand the underlying processes most strongly influencing the sense of wind rotation.

### 3.3 ~~Relative importance~~ Components of ~~tendency terms~~horizontal wind rotation

Expanding the cross product in Eq. (5) using the components of the total wind vector in Eq. (4) the total rate of rotation can be broken into individual forcing terms as follows:

$$\frac{\partial \alpha_{tot}}{\partial t} = \frac{\partial \alpha_{surf}}{\partial t} + \frac{\partial \alpha_{syn}}{\partial t} + \frac{\partial \alpha_{cor}}{\partial t} + \frac{\partial \alpha_{adv}}{\partial t} + \frac{\partial \alpha_{hdif}}{\partial t} + \frac{\partial \alpha_{vdif}}{\partial t} \quad (6)$$

where the subscripts correspond the various tendency components, consistent with terms in Eq. (4). As described earlier, the Coriolis term always induces CR in the Northern Hemisphere. However, the remaining rotation tendency components have much more complex underlying physics, and are discussed individually below.

*Surface Pressure Gradient*: The surface pressure gradient is predominantly driven by the temperature contrast between land and water, and its influence on the sense of rotation depends largely on the location and shape of the landmass. More subtle, local effects of the sea surface temperature inhomogeneity may further alter the turning direction of the surface wind. Moreover, non-uniform surface heating due to topography and irregular coastline of Sardinia are likely to introduce further complexity into surface pressure distribution, as previously suggested by Kusuda and Alpert (1983) .

*Synoptic Pressure Gradient*: As the synoptic pressure gradient term is derived from total pressure gradient it inevitably represents a total of upper level forcings and true synoptic flow. While the synoptic component of the pressure gradient force generally acts in opposition to the surface pressure gradient under SB conditions due to the formation of the SB return flow (Miller et al., 2003) , it also responds to the local topography. Cyclonic and anti-cyclonic rotation may be induced depending on the direction of the local wind and shape of the topography. As SBs are known to develop on all coasts of Sardinia and have variable inland penetration the direction of dominant wind flowing over the primary mountain range on the island is likely to vary throughout the day.

*Advection*: Advection of the horizontal momentum may similarly result in the formation of both CR and ACR. The importance of the term depends largely on the presence of velocity gradients at a given location. Since the regions selected for our analysis are located away from the coast, we can expect the rotational effects of the advection to be of secondary importance.

*Horizontal and Vertical Diffusion*: The horizontal and vertical diffusion are friction driven effects, and hence always act to oppose the local wind. Varying surface roughness due to the spatial distribution of land use, cover and topography may introduce shear and rotation into wind flow. As our analysis is performed for locations away from the coast, these remain largely negligible.

### 3.4 Relative importance of tendency terms

To apply the term-by-term analysis (Eq. 6) to each region identified in Fig. 4, the hourly tendency values for the selected grid points was extracted. They were subsequently normalized by the Coriolis parameter $f$ to produce non-dimensional values, and also spatially averaged amongst the 64 grid-points for each hour. Figure 5 shows the diurnal evolution of the individual terms as well as their spatial standard deviation.

For Region 1 shown in Fig. 5 total clockwise rotation rate increases throughout the day reaching a peak around 15:00 UTC, as may be explained by the growth of the land-sea temperature contrast. As expected, the Coriolis component is one of the leading terms inducing CR, and remains constant. The surface pressure gradient becomes increasingly important through the day, initially contributing slightly to ACR but subsequently turning strongly CR. Note that the surface pressure gradient term includes the combined effects of surface slope, roughness, temperature and pressure gradient and hence is non-zero even though the sub-domain is located over water.

The synoptic gradient acts largely in opposition to the surface pressure gradients, likely due to the formation of SB return flow near 850mb level. As expected this forcing is strongest around 1400. Since the SB return flow often merges with the prevailing synoptic flow and is, hence, difficult to distinguish (Melas et al., 2000) , it is important to highlight that true synoptic winds do not appear to be a significant factor in determining the rotation of the SB. The analysis is based on seven SB episodes that were pre-selected by Furberg (1992) using a fairly conservative filter, ensuring the exclusion of cases with strong overriding synoptic scale winds. The model, similarly, produces very weak synoptic flow, and as evident from Fig. 5 weak synoptic rotational forcing.

Advection effect is always clockwise, but is of secondary importance in this dynamical balance. Horizontal and vertical diffusion terms are largely insignificant in this and the remaining regions, as they were located off the coast where friction is of secondary importance. As SBs are mesoscale phenomena, their scale is not restricted to the immediate coastal region. Hence the analysis can be performed away from the regions of sharp gradients in topography, roughness, and temperature and still capture the dynamics of the phenomenon. Overall, the balance appears to be dominated by surface and synoptic pressure gradients and Coriolis.

While the Coriolis term remains one of the largest in magnitude acting clockwise for Region 2, the combined effects of surface and synoptic pressure gradients outweigh its influence and induce ACR. Similarly to Region 1, a relatively small clockwise advection term is present. While clockwise Coriolis forcing remains the largest term throughout the course of the day the combined anti-clockwise effects of all remaining terms induce ACR in Region 3. A particular feature of the dynamics of this region is that the advection term is relatively important, and without it the ACR would not be possible. Region 4 exhibits largely CR, dominated by the combined effect of Coriolis and pressure gradient terms. Advection and synoptic act to induce ACR, but remain secondary.

It can hence be concluded that the sense of rotation is predominantly a result of local balance of Coriolis, surface and synoptic pressure gradients and advection. While Coriolis forcing remains constant throughout the day, the remaining tendencies each have a unique diurnal pattern. Surface pressure gradient rotation tendency appears to respond faster to the increase in the land-sea temperature contrast, generally peaking in magnitude around noon. The forcing due to the synoptic pressure gradient appears to peak later in the day, which may be explained by the formation of the SB return flow, generally forming with a slight delay in response to the surface SB gravity wave (Miller et al., 2003). The advection term is largest around 15:00 UTC and can act to induce both clockwise and anti-clockwise rotation.

Hence, the dynamical balance of terms contributing to SB rotation in Sardinia appears to be much more complicated than that proposed by Steyn and Kallos (1992) for the Attic Peninsula. The rotation tendencies due to pressure gradients were not typically found to be the largest magnitude terms. Moreover, depending on the specific region of the domain these terms could be acting in the same or opposite directions. This work has shown that, rather than being the result of a simple balance of the synoptic and surface pressure gradients, the sense of direction is determined by whether the combined effects of surface, synoptic and advection tendencies outweigh the Coriolis effect.

The spatial pattern has also proved to be much more complex than that found in Steyn and Kallos (1992). One can speculate that the rotation patterns found around Corsica, which while having a significantly steeper topography closely resembles the single-hill structure of the Attic Peninsula, show a similar ”CR tongue” formation near the eastern coast as found by Steyn and Kallos. However, the accuracy of the simulation was not evaluated in that region, and the proximity to the boundaries of the nest domain do not allow us to draw such conclusions with certainty. The complexity of the spatial patterns of SB rotation in Sardinia may also be explained by the increased ability of newer numerical models to capture detail. An idealized simulation was hence set up to determine whether the complexity of hodograph rotation patterns in Sardinia is associated with the specific topographic features of the island or improved numerical modelling abilities.

## 4 Dynamics of idealized case

It is important to highlight that the idealized case referred to herein is not to be confused with ideal-case WRF simulations, which introduce severe simplification into the model's operation. For this study the full features of a real-case WRF simulation were retained (including all surface, boundary layer and physics routines, as well as real earth features such as curvature and Coriolis). The term *idealized* in this case is meant to indicate that the shape, coastline and topography of the island were generalized to such an extent that they no longer represent the particular characteristics of Sardinia, but rather of any elliptical island with a bell-shaped topography in the mid-latitudes.

Using the standard WRF Preprocessing System (WPS) software to create a domain, the idealized case study was set up with the same parameters and nesting options as the real simulation. The topography was then manually edited to create a perfectly elliptical island in the center of the domain with 40 grid point semi-major axis and 18 grid point semi-minor axis, which approximately matches the size of Sardinia. The remaining grid points of the nest and parent domains were masked as water. All other standard fields such as land use, soil moisture and type, temperature and pressure were also adjusted. The topography height was edited to create a bell-shaped mountain with 800m peak in the center of the island using a 2D Hanning window.

Meteorological data from June 20, 1998 was used to create initial fields with WPS. These were again manually altered to fit the modified domain. Combined domain (including both static and meteorological fields) and boundary files generated by WRF had to be further adjusted to remove any inconsistencies arising due to interpolation. The rest of the simulation was performed using settings identical to the real cases. Since WRF was not designed to introduce idealized topography into a real-case simulation, the results presented in this section cannot be considered conclusive. The complexity of the WRF model makes tracking potential inconsistencies of these modifications extremely difficult. While the hourly patterns of hodograph rotation of the idealized simulation showed distributions nearly as complex as the real-case simulation, the diurnal average shown in Fig. 6 does exhibit a much simpler pattern than that of a real case. ~~Interestingly,~~ It is worth noting that regions of CR and ACR are arranged on opposite coasts to that of the real Sardinia, and similarly to Corsica from the real simulation and the Attic Peninsula from Steyn and Kallos (1992). This coarse pattern of CR and ACR rotation can likely be attributed to similarities between the shape and elevation of the gross topography of the Attic Peninsula and the gross topography of the idealized simulation. A consequence of this is that the more complex CR and ACR patterns in the real simulations are a product of quite local topographic influences.

Overall the structure appears to be vortex-like, centering around the peak of the mountain. One can speculate that the region of CR on the eastern coast of the island is the equivalent of the ”CR tongue” feature of Attic Peninsula. Again, further model analysis would be necessary to confirm this finding.

The term-by-term dynamical analysis for the idealized simulation is also much less conclusive then that of the real simulation. The west-coast ACR region shows consistent but relatively weak total rotation forcing, as seen in Fig. 7. Early morning values appear to be unrealistically large. This may be an indication of a model response to the morning switch in the direction of surface heat flux, which in some cases produces a spike in model fields. As likely inconsistencies in the domain set-up due to modification of the standard preprocessing routine may reduce the numerical stability of the model, the increased values caused by a spike may persist for long periods of time. Overall the dynamics of the ACR region mimic those of Region 3 in the real case simulation, with all significant terms acting to counterbalance Coriolis forcing. Since idealized Region 1 remains away from the coast the diffusion terms are again insignificant. Unlike the real case simulation the afternoon surface, synoptic pressure gradients and advection are all of approximately the same magnitude.

The CR region on the eastern coast (Region 2) of the idealized island shows much stronger rotational tendency than that on the western coast. The signs of surface and synoptic pressure gradient vary throughout the day. Similarly to idealized Region 1, pressure gradient and advection terms have like magnitudes. As this region partially covers land grid points vertical diffusion term can no longer be ignored. Friction effects contribute to the total balance inducing both clockwise and anti-clockwise rotation depending on the time of the day. Similarly to the real case, the overall shape of the total diurnal rotation curve appears to be strongly influenced by that of the surface pressure gradient. Though Region 1 of the idealized simulation has a similar spatial variability to that of the real case simulation, larger standard deviation values were observed for the second region.

While these results generally appear to be in agreement with the previous studies further evaluation is necessary to deem the findings conclusive. The patterns of clockwise and anti-clockwise hodograph rotation are notably simpler than that of a real-case simulation, as anticipated. While the distribution of CR and ACR regions bears little resemblance with that of real Sardinia, the underlying dynamical behavior appear similar.

## 5 Conclusions

This study examined the dynamics of SB rotation in a region of complex topography, with known occurrence of both theoretically expected CR as well as ”anomalous” counter-Coriolis ACR. A numerical simulation was performed for Sardinia, using the WRF Model and subsequently evaluated for accuracy using local observations. The original WRF-ARW code was adjusted to allow for the extraction of the individual components of the horizontal momentum equations from the solver. Observed and simulated daily hodographs were compared and an evaluation methodology was devised to asses WRF's ability to capture SB kinematics. The diurnal evolution of modelled and observed onshore winds was shown to be in strong agreement.

Terms found to have significant contribution to the total momentum balance over the domain included pressure gradient (subsequently separated into surface and synoptic components), Coriolis, advection, and horizontal and vertical diffusion. The rate of rotation of the total horizontal momentum tendency was plotted for the entire domain. Following Kusuda and Alpert (1983), the strength of rotation due to each component of the horizontal momentum equations was determined for the selected regions around the island. The direction of rotation was found to be a result of a complex interaction between surface and synoptic pressure gradients, Coriolis and advection.

Lastly, an idealized simulation was attempted using a similar domain configuration as that of a real case, but introducing a completely artificial simplified topography.Contour maps of regions of CR and ACR showed the formation of a vortex-like region of ACR around most of the island, with a single protruding ”tongue” of CR region in the middle of the East coast. The dynamical analysis of regions of CR and ACR showed that the balance of forces resembled those of the real simulation, however, higher variability as well as unlikely individual term magnitudes suggest that the simulation requires further improvements to be considered conclusive.

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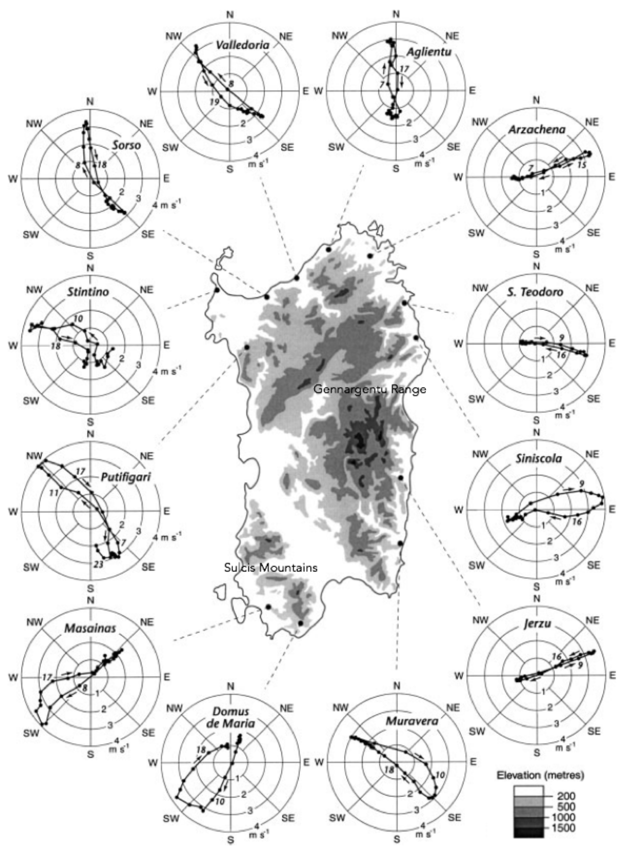


**Fig. 1.** Topographic map of Sardinia with 12 coastal stations and SB hodographs. The island is approximately 270 km long and 140 km wide,from Furberg et al. (2002)

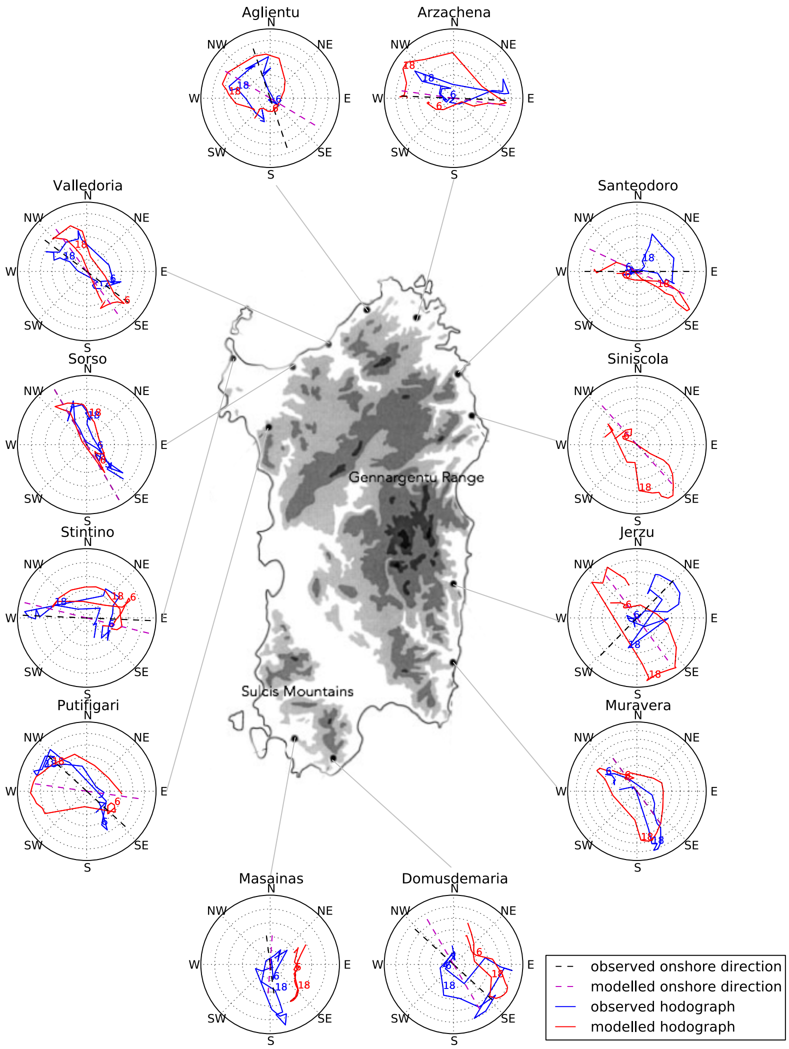


**Fig. 2.** Modelled and observed wind hodographs at 10m over Sardinia on June 21, 1998

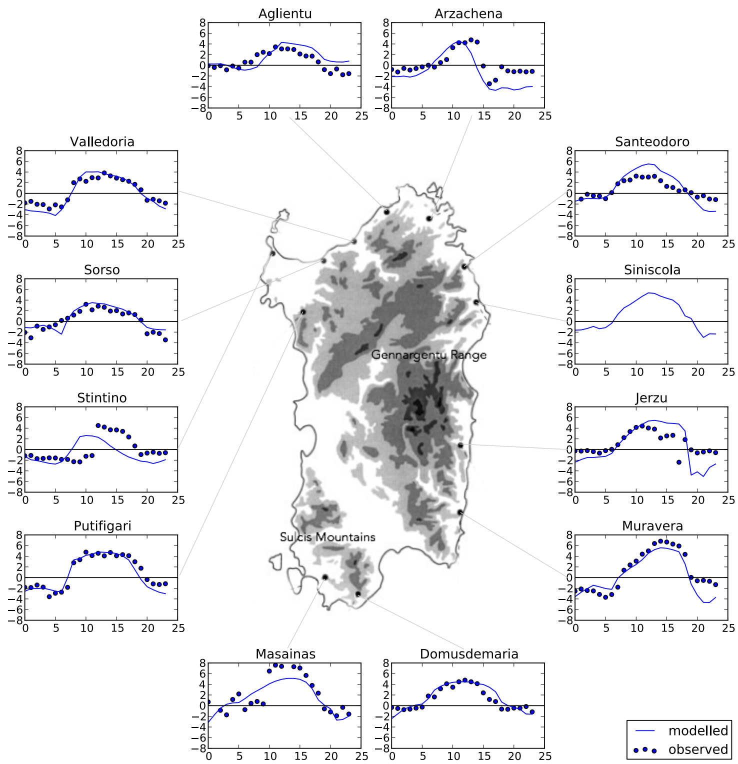


**Fig. 3.** Diurnal evolution of onshore wind at 10m over Sardinia on June 21, 1998

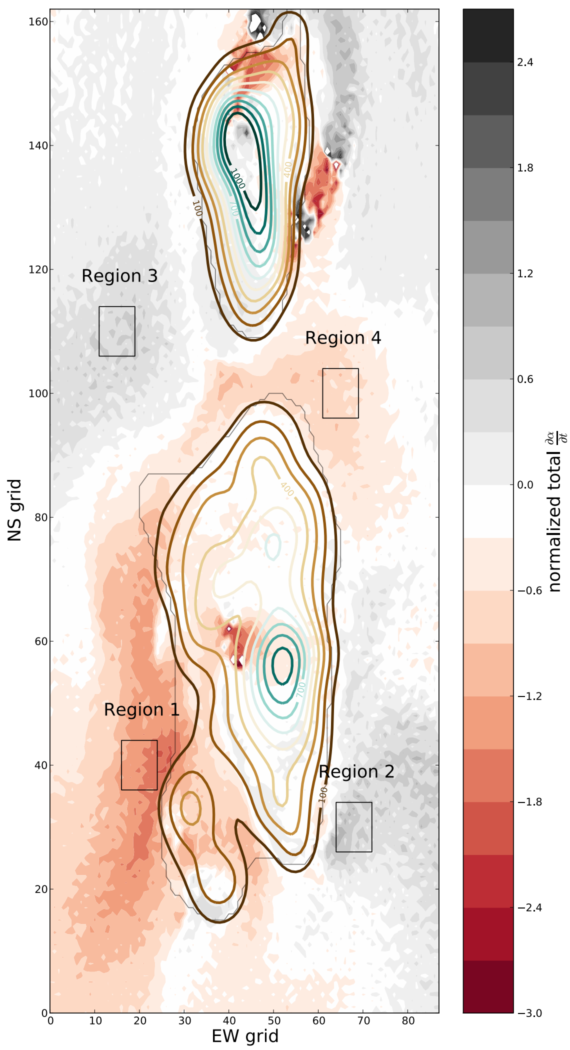


**Fig. 4.** Total $\frac{\partial\alpha}{\partial t}$, averaged over daytime hours. Also shown: smoothed elevation contours, smoothed coast line, Regions 1,2,3 and 4 are identified for further dynamical analysis

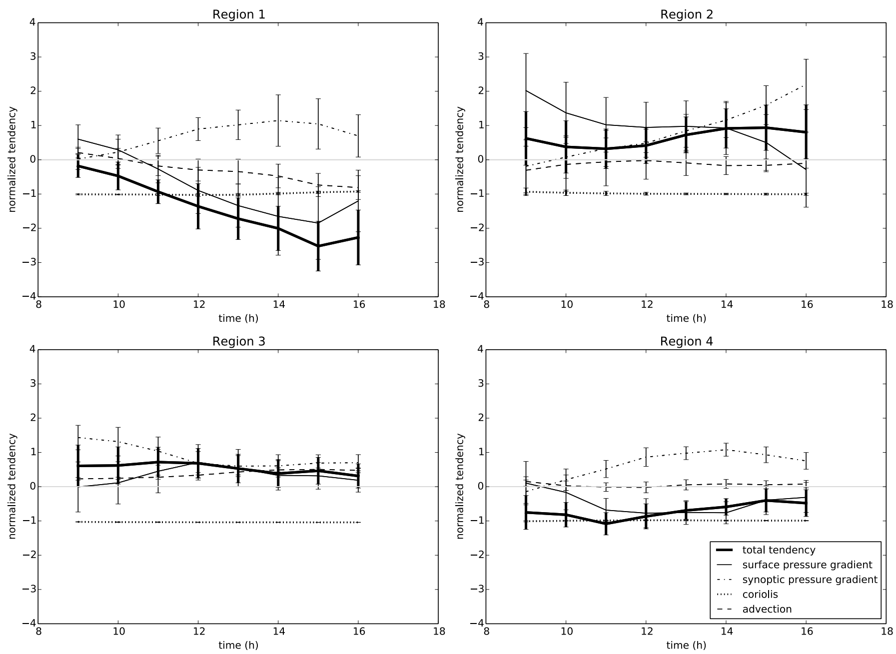


**Fig. 5.** Evolution of dominant dynamic forcings for Regions 1,2,3 and 4, on June 20, 1998. Positive and negative values correspond to ACR and CR, respectively.

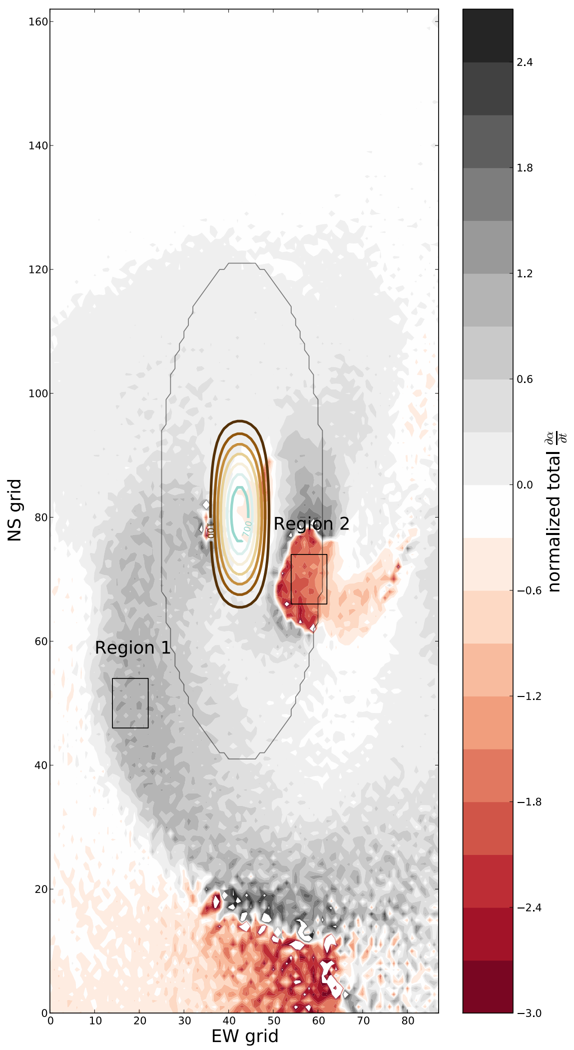


**Fig. 6.** Total $\frac{\partial\alpha}{\partial t}$ values are averaged over daytime hours. Also shown: elevation contours, coastline, Regions 1 and 2 are identified for further dynamical analysis

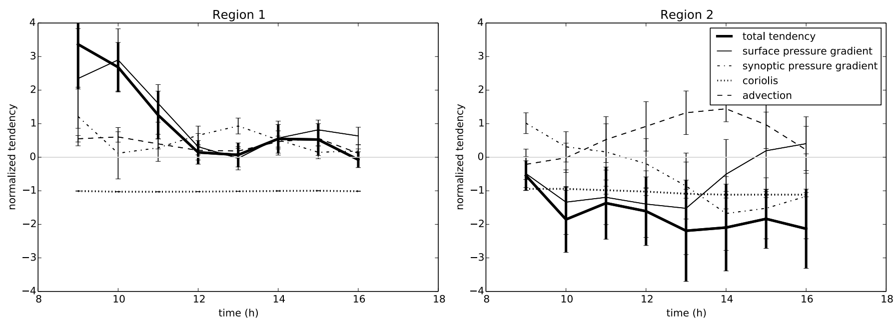


**Fig. 7.** Evolution of dominant dynamic forcings for Regions 1 and 2, idealized case. Positive and negative values correspond to ACR and CR, respectively.