Master's Thesis Proposal

COSMO Model Performance in Forecasting Foehn: a Systematic Process-oriented Verification

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Summary

Strong foehn episodes can develop into violent windstorms capable of causing severe material damages. Accurate forecasts of foehn strength, duration and extent are essential for preventative and protective measures against losses to be effectively taken. Foehn is forced by strong synoptic-scale flow that develops nearly perpendicular to mountain ranges, such as the Alps. The flow characteristics of foehn are, thus, highly dependent on local topography and are challenge to predict. High-resolution numerical prediction models, such as COSMO-2, are needed to resolve the topography and mesoscale flow of the Foehn to predict it accurately. However, different foehn case studies and subjective model verifications suggest that the COSMO-2 model has several deficiencies when forecasting both south and north foehn episodes in the Swiss Alps. We propose a systematic assessment of errors in COSMO-2 foehn forecasts. This will be done through a process-oriented verification with 1-2 years of observational data from automatic surface stations in Switzerland. The following aspects of foehn in COSMO-2 will be quantitatively assessed: breakthrough and termination (temporal and spatial extent), intensity (mean wind and gusts), biases of relative humidity and gradients of potential temperature, and pressure. The results will give an objective indication of the COSMO-2 model performance.

Contents

1.0 Background

1.1 Motivation

Foehn, a dynamic downslope wind phenomenon, has captivated the interest of scientists for over a century. Foehn winds occur in the presence of strong synoptic-scale flow that develops across mountain ranges, such as the Alps. Consequently, the flow characteristics of foehn are highly dependent on local topography and are thus unique to each Alpine valley, making them a challenge to predict (Drobinski et al., 2007). Local air quality, surface air temperature and humidity are strongly influenced by the presence of foehn. In addition, strong foehn episodes can develop into violent windstorms capable of causing severe material damages. Therefore, accurate forecasts of foehn strength, duration and extent are essential for preventative and protective measures to be effectively taken.

1.2 Characteristics of foehn

WMO (1992) defines foehn as "wind [which is] warmed and dried by descent, in general on the lee side of a mountain." In essence, air, forced by strong, synoptic-scale pressure gradients at low altitudes (FIG. 1), flows perpendicularly or quasi-perpendicularly over the ridges of a mountain range. Though both can occur simultaneously, the following foehn mechanisms can be distinguished:

1. In cases where air masses are completely or partially lifted at the windward side of a mountain ridge: air parcels are forced to ascend as they are advected up the windward slope of a mountain. As the air parcels expand and cool with increasing altitude. Water vapour then condenses once the dew-point temperature is reached. Latent heat is released as a result (condensational heating), and allows air parcels to cool at the moist adiabatic lapse rate (~6ºC/km altitude). Precipitation then occurs on the windward side and lowers the humidity of the advected air parcels. Like in the previous mechanism, the air then descend down the lee slope, accelerate, thin and warm due to adiabatic compression. This foehn mechanism is found mainly in the Swiss Alps.

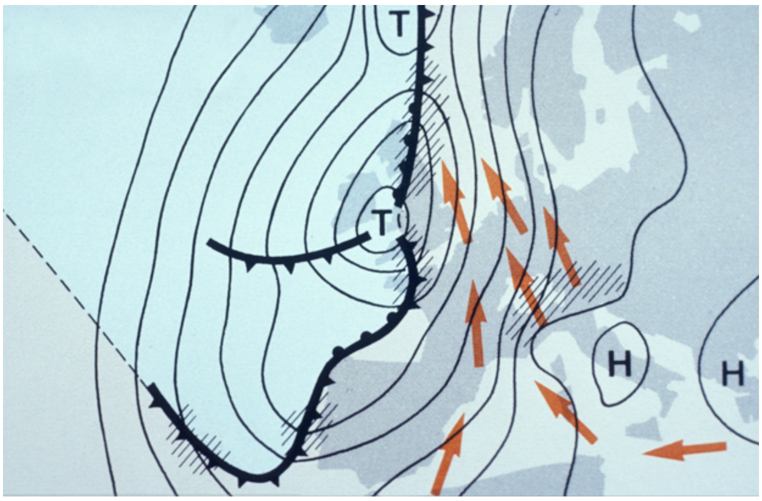

FIG. 1. *Surface weather analysis chart of central Europe depicting typical synoptic-scale conditions during south foehn episodes over the Alps. Solid lines are lines of constant surface pressure (isobars). Red arrows indicate approximate surface wind direction.* ***T*** *indicates the centre of a low-pressure system.* ***H*** *indicates the centre of a high-pressure system. Warm and cold fronts are shown with thick black lines. (Richner and Haechler, 2008)*

2. In cases where a capping inversion is present on the windward side of a mountain ridge: ascent of air parcels below the ridge is inhibited by a capping inversion at the top of the planetary boundary layer (PBL) and, consequently, the flow is blocked from advection by the mountain range (Baumann et al., 2001). Air parcels at or above the inversion layer descend down the lee slope (FIG. 2), accelerate, thin, and warm due to adiabatic compression (~10ºC/km altitude) (Hann, 1866). In addition, turbulent mixing homogenizes the air mass and leads to neutral stratification. It follows that a significant increase in temperature and decrease in relative humidity is then observed along the lee slope of the mountain range. This foehn mechanism occurs more often, particularly in the Austrian Alps.

Foehn flow is often channelled through gaps in the ridges and valleys within the mountain range, such as the Brenner Pass (Wipp Valley), the Gotthard Pass (Reuss Valley), the San Bernardino Pass (Rhine Valley) and the Simplon Pass (Rhone Valley) (Seibert, 1990). This flow restriction induces an increase in wind speed and a decrease in pressure (Bernoulli Effect). Concurrently, turbulent mixing occurs along the slope and at the stable interface (between the air aloft and the foehn flow) due to surface friction and vertical wind shear, respectively. Further downstream, the strongest mixing occurs at the hydraulic jump. The hydraulic jump develops once the foehn wind speed slows to subcritical velocities (Durran, 1990).

Foehn flow breaks away from the slope surface once it achieves the level of neutral buoyancy. Frequently, the level of neutral buoyancy corresponds with the top of a cold air mass. Such cold pools form at night and are occasionally eroded by the incoming foehn front. In areas where foehn breakthrough is not achieved, the foehn air mass acts as a capping inversion that traps the pollutants below (Drechsel and Mayr, 2008).

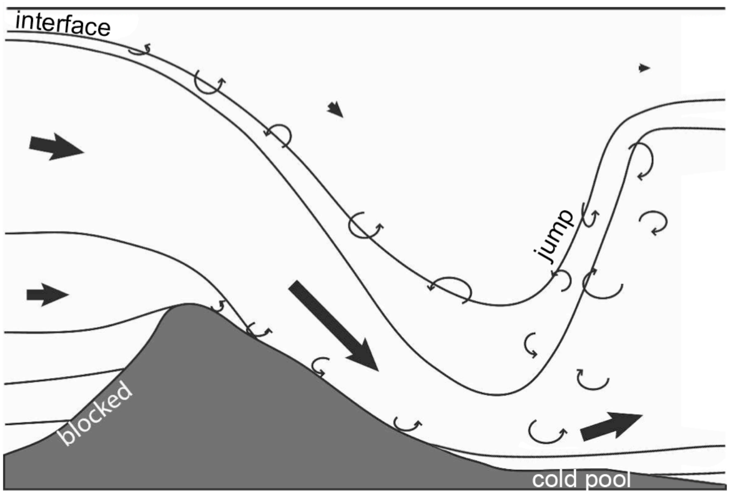

FIG. 2. *Cross-section of a typical foehn episode as a result of synoptic-scale flow over a mountain ridge in the presence of an inversion. Solid lines are lines of constant potential temperature (isentropes). Curved arrows indicate turbulent mixing. Solid arrows show the qualitative wind speeds. The areas of stable air-interface, orographic blocking, hydraulic jump, and cold air pool are labelled (Drechsel and Mayr, 2008)*

1.3 Probabilistic diagnosis of foehn episodes

Foehn episodes frequently manifest dramatic changes of potential temperature, humidity, wind speed and gust magnitude. Indeed, changes in these parameters serve as indicators and predictors for foehn diagnosis (nowcasting) and forecasting, respectively. However, distinguishing between foehn and other atmospheric phenomena such as thunderstorm outflows or strong nocturnal down-valley winds is difficult (Drechsel and Mayr, 2008). In the past, foehn nowcasting methods were principally based on the orientation of the synoptic pressure field. However, due to the unique orientations and topographies, the occurrence and strength of foehn in individual valleys was uncertain. In the last decade however, more objective methods of foehn detection have been developed.

Duerr (2008) developed a method for nowcasting south foehn that exploits the lee slope decent of isentropes. This algorithm has been in use at the Swiss Federal Office of Meteorology and Climatology (MeteoSwiss) since July 2008. The method, derived from real-time, observational data from 1991-2000, is fully automated. Differences in potential temperature between surface weather stations and a reference station near the Alpine ridge are calculated. The probability of a foehn episode occurring near a station is thus a function of the magnitude of the potential temperature gradient. However, the validity of this method is restricted to valley floors or near valley outlets where, to some extent, foehn flow is channelled. Furthermore, inhomogeneities in observational data can distort nowcasting of foehn episodes due to rigid thresholds within the method (Duerr, 2008).

Gridded model-analysis datasets do not suffer from such observational inhomogeneities. Drechsel and Mayr (2008) developed a method based on global forecast model T511 from the European Centre for Medium-Range Weather Forecasts (ECMWF). Thus, it is a more objective, probabilistic method for foehn nowcasting. The combined indicators — isentropic decent and cross-barrier pressure differences — provide a mesoscale (2-2000km horizontal scale) fingerprint of a foehn episode. These parameters were tested against three years of observational data from surface weather stations in the Wipp Valley (Austrian Alps). The joint probabilities of these parameters show a higher skill of foehn nowcasting than the probabilities of the separate parameters. Moreover, this nowcasting method can be applied to locations where topography is insufficiently resolved by general circulation models (Drechsel and Mayr, 2008).

1.4 Probabilistic forecasting foehn

Foehn forecasts are realized when nowcasting methods, such as those previously described, are applied to numerical weather prediction (NWP) model analysis data rather than real-time observational data. Drechsel and Mayr (2008) have shown that objective foehn episode forecast skill is high for lead times as long as three days. The predictability is high for a γ-mesoscale (2-20km horizontal scale) phenomenon, such as foehn, despite being modeled with a 40km resolution. However, higher resolution NWP models are required to simulate complex topography of alpine valleys, which were previously not well resolved, thereby enabling accurate prediction of foehn flow dynamics.

1.5 COSMO-2 model and foehn forecasting deficiencies

Since February 2008, MeteoSwiss has operated a high-resolution model from the Consortium for Small-Scale Modelling (COSMO). COSMO is based on the primitive thermo-hydrodynamic equations that describe non-hydrostatic (vertical movement), compressible flow in a moist atmosphere. The model utilizes a rotated geographical Arakawa C-grid and generalized terrain-following height coordinates with a Lorenz vertical staggering scheme. Prognostic variables include: vertical and horizontal wind components, pressure perturbation, temperature, specific humidity, cloud water and ice content, rain, snow, and turbulent kinetic energy. Diagnostic variable include: total air density and fluxes of rain and snow. COSMO applies the following to all runs: a third-order spatial discretization and 2 time-level time integration based on Runge-Kutta split-explicit scheme and Rayleigh damping in the upper layers (Dierer, 2009). COMSO is also coupled to a multi-layer soil model utilizing 8 and 6 layers for energy and moisture fluxes, respectively. Moisture values in the lowest levels are updated every 24h from IFS.

Several differences between the parameterizations of COSMO-2 and COSMO-7 exist. In COSMO-2, convection is parameterised by a shallow convection scheme while deep convection in COSMO-7 is explicitly computed. Moreover, topographic effects on incident radiation are considered while they in COSMO-7 they are not. Finally, COSMO-2 has a microphysical parameterization that uses a prognostic graupel hydrometeor class.

COSMO contains a Newtonian relaxation algorithm that facilitates observational data assimilation. In essence, the simulated atmospheric fields are forced towards observations at the time of the observation by a nudging function. The following in-situ data are assimilated from (MeteoSwiss, 2009):

- Surface synoptic stations, ship and buoy measurements
  - Surface pressure
  - 2m humidity for the lowest model level
  - 10m wind for stations below 100m above msl
- Temp/pilot data
  - Wind
  - Temperature
  - Humidity profiles
- Aircraft (AIREP/AMDAR) measurements
  - Wind
  - Temperature
- Wind profiler data
- A snow analysis, derived from MSG satellites combined with dense observations

Additionally, COSMO-2 assimilates Radar-derived rainfall data via latent heat nudging. This scheme utilizes high spatial and temporal resolution of the rainfall observations. Rainfall data is obtained from three C-Band Radars in the Swiss Radar Network. The assimilation cycle is run in 3-hour intervals and a 45-minute observation cut-off time. COSMO is run with three nested domains with increasing horizontal resolution. The global Integrated Forecast System (IFS) model from ECMWF drives lateral boundary conditions for COSMO-7, which extends over Western Europe. COSMO-7 then provides lateral boundary conditions for COSMO-2, which covers the Alpine arch (FIG. 3). This configuration allows COSMO to provide short-range forecasts at mesoscale resolutions in relatively short computational times. Forecasts, which begin every 3 hours, are integrated up to 24 hours in a rapid update cycle.

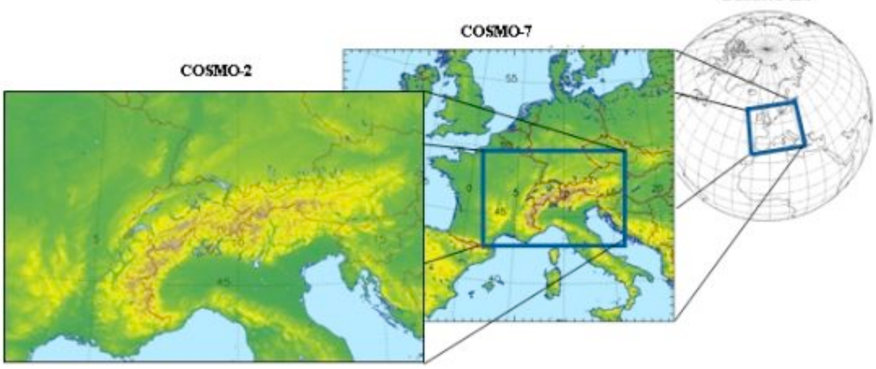

FIG. 3. *The three nested NWP model domains of the COSMO system as operated by MeteoSwiss.* ***Left:*** *COSMO-2 model describing the local scale.* ***Middle:*** *COSMO-7 model describing the regional scale in Europe.* ***Right:*** *ECMWF operates a global NWP model describing the synoptic scales. (MeteoSwiss, 2010)*

Although upper-level wind fields are represented quite well in COSMO-2, there are several deficiencies in the simulation of typical foehn patterns in the Planetary Boundary Layer (PBL). This can often lead to forecast problems for both south and north foehn episodes. A foehn case study by Burri et al. (2007) indicates for example that foehn mean/gust wind speeds in COSMO-2 are underestimated despite generally accurate pressure gradients. Additionally, there is a negative temperature bias during foehn episodes, which is likely a result of too weak decoupling of air and soil temperature in the model (Duerr, 2010). Lastly, foehn breakthrough, termination and geographical extension are poorly represented. An objective, quasi-climatological systematic assessment of these forecast errors is the basic step in order to improve the forecasting skill of foehn in the COSMO-2 model.

2.0 Objectives

We propose a systematic assessment of errors in COSMO-2 foehn forecasts. This will be done through a process-oriented verification with 1-2 years of observational data from automatic surface stations in Switzerland. The following aspects of foehn episodes in COSMO-2 will be quantitatively assessed:

- How well is foehn breakthrough and termination (temporal and spatial extent) represented?
- How well is foehn intensity (mean wind and gusts) represented?
- What are model biases of gradients of relative humidity, potential temperature, and pressure?

The above will yield a comprehensive and objective error assessment of the climatological performance of foehn in the COSMO-2 model. Thereby, allowing further improvements to sub-grid scale parameterizations to be done to better represent foehn episodes. An auxiliary task will be to perform several foehn case studies within the Swiss Alps (e.g. Rhine Valley) to assess which atmospheric parameters prove to be good foehn predictors.

3.0 Data and methods

3.1 Observational and model analysis datasets

MeteoSwiss shall provide 1-2 years of both observational data and COSMO-2 model analysis data. Observations are collected by a national network of automated surface weather stations (SwissMetNet) that are distributed across Switzerland (FIG. 4). Several of these stations provide hourly measurements of temperature, relative humidity, wind speed and wind direction during foehn episodes. However, the majority of stations provide measurements every 10 minutes. The COSMO-2 analysis data are available in a gridded format covering all of Switzerland. From these gridded data, we shall interpolate all information related to the SwissMetNet stations with different grid-point selection or association methods. Based on the surface network, automatic foehn detection can be applied to both observational and model analysis data.

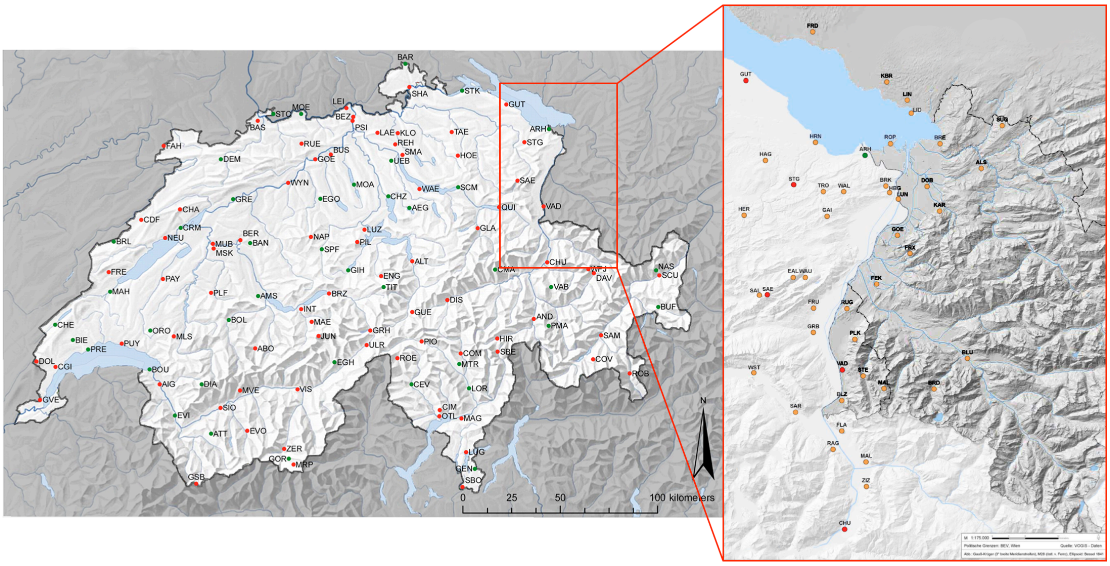

FIG. 3. *Locations of automatic surface stations in Switzerland and the Lake Constance region.* ***Left:*** *Station network operated by MetoSwiss (SwissMetNet) as of August 18th, 2009. Green dots indicate hourly data supply. Red dots indicate data supply every 10 minutes.* ***Right:*** *Station network in the upper Rhine Valley and Lake Constance region operated by AFG are indicated by orange dots. Note: 46 out of 61 are shown along with six SwissMetNet stations. (MeteoSwiss, 2009, Burri et al., 2007).*

An additional dataset is may be available from the Alpine Foehn Research Group Rhine Valley/Lake of Constance (AGF). This dataset is from a dense network of automated surface weather (FIG. 4) and radiosonde stations, several types of remote-sensing instruments as well as research aircraft throughout the Rhine Valley/Lake Constance area.

3.2 Categorical verification

A classification scheme is needed to sort the observational data according to a binary event (foehn or no-foehn) using the mentioned above automatic foehn detection. Another classification scheme can be implemented for model data. For example some elements of the nowcasting method developed by Drechsel and Mayr (2008) previously mentioned can be used and tested. An arbitrary foehn probability (90%) shall be chosen as the classification threshold. Thresholds values of differences in potential temperature ($\Delta\Theta$) and surface pressure (Δp) between weather stations and a reference station near the Alpine ridge shall be determined from the joint probability distribution. Based on these thresholds, the data shall be sorted into binary categories of foehn and no-foehn. Simple categorical scores, such as the probability of detection (POD) and false alarm ratio (FAR), will be used to quantify this type of verification:

$$POD = \frac{hits}{observed\ events} \tag{1}$$

$$FAR = \frac{false\ alarms}{forecasted\ events} \tag{2}$$

A similar categorical approach can be applied for other more dangerous events (gusts above a certain threshold).

3.3 Traditional verification

For the COSMO-2 model validation, we shall compare COSMO-2 analysis datasets with observational datasets of temperature, relative humidity, wind speed and wind direction during foehn episodes. In keeping with the methods of Gohm et al. (2004), quantitative simple error scores will be calculated between each model and observational parameter on a temporal and spatial scale. The model bias represents the average direction of the deviation between the two datasets and is calculated with the following mean error formula:

$$ME = \frac{1}{M}\sum_{j=1}^{M} \frac{1}{N}\sum_{i=1}^{N} (A_{i,j} - B_{i,j}) \tag{3}$$

Where A and B represent one parameter of the model and observational datasets, respectively. The ME is calculated for a period of M time steps and for a field of N grid points. The ME will be negative if, on average, dataset A underestimates dataset B. Furthermore, special attention will be given to quantify the seasonal variation in the model bias.

The average magnitude of the error between the two datasets is calculated with the following root mean squared error formula:

$$RMSE = \sqrt{\frac{1}{M}\sum_{j=1}^{M} \frac{1}{N}\sum_{i=1}^{N} (A_{i,j} - B_{i,j})^2} \tag{4}$$

Where A and B represent one parameter of the model and observational datasets, respectively. Here, the RMSE is calculated for a period of M time steps and a field of N grid points. The above scores will be used to verify the model performance in each station as well as each well-defined target region (e.g. The Rhine Valley).

3.4 Special verification

Other typical aspects of foehn episodes such as foehn breakthrough and termination, duration, may be evaluated separately. A strategy for this type of verification must be developed.

4.0 Timeline

Weeks	Length	Activity
1-2	½ month	Literature Review
Milestone I		Basic knowledge of the COSMO model. Understand physical aspects of the problem
3-6	1 month	Adapt and/or prepare programs/tools for reading/visualize/plotting data
Milestone II		Can read and visualize observations and model data (gridded and point data). Choose 1-3 case studies and analyze them.
7-14	2 months	Development of the verification strategy and verification of the COSMO model over 1-2 years
Milestone III		Definition of the verification strategy and preparation of the tools or the software to execute it
13-16	1 month	Writing and submitting master thesis, chapter by chapter, for review.
Milestone IV		Whole master thesis written and revised
17-20	½ month	Correct and incorporate revisions.

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