WMO TRAINING MATERIALS AND BEST PRACTICES FOR CHEMICAL WEATHER/AIR QUALITY FORECASTING (CW-AQF)

WEATHER CLIMATE WATER
TEMPS CLIMAT EAU

A. Baklanov (1) and Y. Zhang (2)
(1) Science and Innovation Department, World Meteorological Organization (WMO), Geneva, Switzerland
(2) Department of Civil and Environmental Engineering Department, Northeastern University, Boston, MA 02115, USA
Presenting author email: abaklanov@wmo.int

Virtual PAPILA Summer School, 20 - 24 April 2020
Sponsors: The EU PAPILA Project, MAP-AQ (IGAC and WMO)
The University of Chile in Santiago and the Max Planck Institute for Meteorology in Hamburg

WMO OMM
World Meteorological Organization
Organisation météorologique mondiale

GAW

Outline of the Lecture

- WMO Global Atmosphere Watch (GAW) Mission and Focus for L. America
- Importance and Types of Application of RT CW-AQF
- Introduction to the CW-AQF Training Book
- History and Current Status
- Performance Evaluation
- Methods for Improvement of RT-AQF
    - Scientific Advancements
    - Numerical and Computational Techniques
- Impact Based Forecasting and Fit-for-Purposes Approach
- Major Research Challenges
    - Model Development and Improvement
    - Inputs, Outputs, and Community Outreach

Sources: GAW IP (2017), Zhang et al. (2012a, b) and Zhang & Baklanov (Eds.) 2019

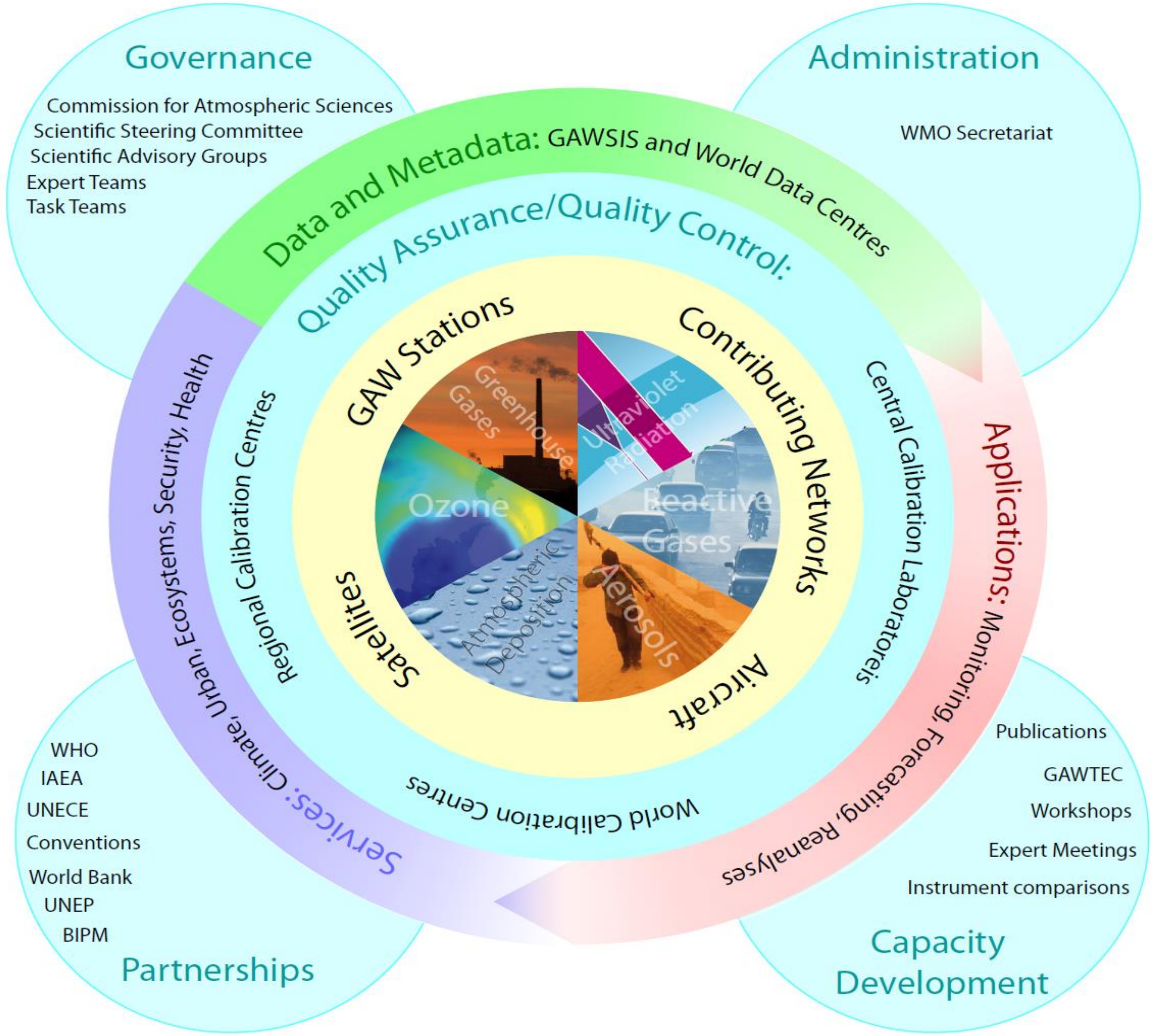
WMO Global Atmosphere Watch (GAW) Mission

Systematic long-term monitoring of atmospheric chemical and physical parameters globally

Analysis and assessment

Development of predictive capability

(GURME, APP SAG and Sand & Dust Storm Warning System) for chemical weather (e.g. incl. air quality, SDS, biomass burning, volcanic ash, etc.)



WMO OMM

WMO GAW stations in Latin America

- There is a very limited dataset of continuous high-resolution observations available for South America (15 are operational with data submission, 20 are non-reporting and 12 are closed) - statistics includes all parameter.
- WHO database contains usually annual averages and it is not appropriate for air quality forecasting.
- Argentina operates GAW Regional Calibration Centre and they had a comparison campaign for surface ozone analysers. 3 surface ozone instruments were brought by EMPA to substitute broken ones.
- The sites participated in the campaign:
  - Bs As (Argentina) 2 instruments
  - La Quiaca (Argentina) 1
  - Marambio (Argentina) 1
  - Pilar (Argentina) 1
  - Ushuaia (Argentina) 1
  - San Lorenzo (Paraguay) 1
  - Salto (Uruguay) 1
  - El Tololo (Chile) 1
  - Natal y Arembepe (Brasil) 2
  - Chacaltaya (Bolivi) 1
  - Paramaribo (Suriname) 1
  - Manaus (Brasil) 1

GALION: GAW Lidar & Ceilometer Observation Network

The Latin America Lidar Network (LALINET a.k.a ALINE) is a Latin American coordinated lidar network, established in 2001, measuring aerosol backscatter coefficient and aerosol extinction profiles for climatological studies of the aerosol distribution over Latin America, as well as other atmospheric species such as ozone and water vapor. This federative lidar network aims to establish a consistent and statistically sound database for enhancement of the understanding of the aerosol distribution over the continent and its direct and indirect influence on climate.

- **LALINET web-site: http://lalinet.org/**

They have 16 sites

- **Some data can be used from IAGOS/Caribic**

http://www.caribic-atmospheric.com/
https://www.iagos.org/
IAGOS is also a contributing network to GAW

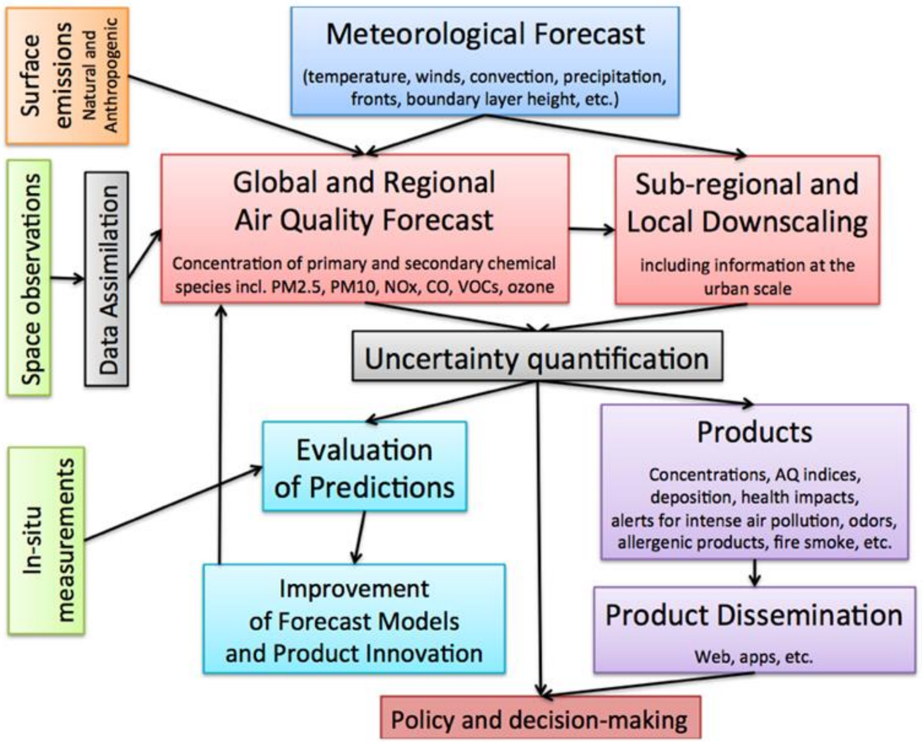
<= L. America on the Global map of operational ceilometers (October 2017) as reported at http://www.dwd.de/ceilomap. Different colors are for different manufacturers.

- **11th Workshop on Lidar Measurements in Latin America, November 16 –20, 2020 / Punta Arenas, Chile,** https://xiwlmla.umag.cl/

GAW – Enhancing Modeling

The broad "atmospheric chemistry" application area was substituted with more specific application areas:

- "atmospheric composition forecasting",
- "atmospheric composition analysis and monitoring"
- "urban services".



Expand GAW's role in enhancing predictive capabilities (atmospheric composition & its uses)

☑ Urban air quality forecasting capabilities through GURME,

☑ Modelling Applications SAG ("Apps") – global and regional AQF: focus on science and new developments

☑ MAP-AQ: Monitoring, Analysis & Prediction of Air Quality (with IGAC)

☑ GAFIS: Global Air Quality Forecasting & Information Systems: R&D for operational services

☑ SDS-WAS: Sand and Dust Storm Warning Advisory and Assessment System

☑ Seamless CCMM and Earth System modelling (WGNE, etc)

Capacity building, training and education aspects

- **Joint work of WMO Education & Training Office and GAW Programme (APP and GURME SAGs, GAFIS, MAP-AQ, SDS-WAS, VFSP-WAS)**
- **Develop long-lasting training books:** Training Materials and Best Practices for Chemical Weather /Air Quality Forecasting (CW-AQF), 587 pages, 82 authors, edited by Y. Zhang and A. Baklanov, 2019, sponsored and to be published by WMO
- **Organize annual training workshops on different continents in developing countries** (e.g., 2019 October training workshop on RT-AQF in Nairobi, Kenya with > 40 participants from 16 countries)
- **Sponsor training in established research laboratories and regional training centers (e.g., Europe, North America, Africa)**

WMO Training Materials and Best Practices for Chemical Weather /Air Quality Forecasting (CW-AQF)

World Meteorological Organization (WMO)
Research Department
Global Atmosphere Watch (GAW) Program
Education and Training Office

Draft version is available from:
https://elioscloud.wmo.int/share/s/WB9UoQ5kQK-dmgERjSAqIA

Training Materials and Best Practices for Chemical Weather/Air Quality Forecasting (CW-AQF)

Final Version

Scientific Editors:
Yang Zhang and Alexander Baklanov

May 4, 2019

Background

- **Increasing needs for CW-AQF with increasing number of forecasters worldwide, increasing involvements of NMHSs**
- **Increasing complexity of the 3-D numerical models for CW-AQF with recent scientific advancements in numerical weather prediction (NWP) and CW-AQF**
- **Common mistakes leading to unsuccessful implementation and application**

Overarching goals

- **Provide best existing experience from NMHSs and academic community to build scientific capacity of researchers and operational meteorologists in developing countries through bridging sciences into operations**
- **Make sustained contributions towards the implementation of relevant policy and decision support aimed at improving quality of life through enhancing the science-policy interface**

Specific Objectives

- **Help forecasters worldwide, especially those in developing countries on using 3D CW-AQF models for best practices and operations**
- **Provide practical information about the best CW-AQF practices and standardized procedures for the successful deployment and application**
- **Prepare materials that could be adapted for training by NMHSs, WMO training centers, and other users from environmental authorities and academic institutions**

Real-Time Chemical Weather-Air Quality Forecasting (RT CW-AQF)

Importance and Types of Applications

- Air pollution levels are not decreased anywhere in anytime
  - Urban pollution levels decrease, but regional pollution has increased
  - Little or no improvement in AQ in some underdeveloped countries
- Public awareness of AQ increases despite decreased air pollution
  - Especially for sensitive subpopulations: children, elderly, asthmatics
  - Public reporting of observed AQ levels (e.g., AIRNow, news media)
- Emission reduction programs triggered by high pollutant levels
  - Rely on short-term forecasts of O_3, CO, $PM_{2.5}$, and visibility
- Climate change mitigation and integration with AQ management
  - Rely on long-term forecasts of greenhouse gases and PM species
- Types of Applications of RT CW-AQF Products
  - Public health notification
  - Episodic control programs (e.g., Ozone Action Days)
  - Scheduling specialized air monitoring programs
  - Deployed during major sport events (e.g., the 2008 Olympic Games in Beijing and the 2010 Commonwealth games in Delhi) and political summits (e.g., the G-20 in Hangzhou)

History and Overview

World Meteorological Organization (WMO)
Research Department
Global Atmosphere Watch (GAW) Program
Education and Training Office

Training Materials and Best Practices for Chemical Weather/Air Quality Forecasting (CW-AQF)

Final Version

Scientific Editors:
Yang Zhang and Alexander Baklanov

May 4, 2019

- Initiated in May 2017 with Yinka Adebayo
- Sponsored by the WMO's Education and Training Office and the GAW Program, with support from GURME
- Developed an outline, Jun-Dec, 2017
- Developed preliminary draft, Jan-May 2018
- Review by APP & GURME SAGs, May-Oct 2018
- Developed final draft, Sep 2018 – Apr 2019
- Submitted final draft, May 2019
- Published online in Sep 2019, will be updated as an effective, long-lasting educational and outreach tool
- **12 Chapters, 539 pages, 49 tables, 111 figures**
- **82 authors from 15 countries**
- **17 Global and 51 regional CW-AQF models**
- **24 demonstration cases** over Global (3), Europe (4), **North America (3),** Asia (5), **South America (2),** Oceania (3), and Africa (4)

Acknowledgements

- **Sponsors:** the WMO's Education and Training Office and the Global Atmosphere Watch (GAW) Program, with support from the Scientific Advisory Groups on Applications (GAW SAG APP) and GAW Urban Research Meteorology and Environment (GURME). In particular, we acknowledge the initiative and support from Yinka Adebayo, the Director of Education and Training Office.
- **Lead authors**: K. Wyat Appel, Alexander Baklanov, Jason Ching, Johannes Flemming, Edmilson Freitas, Carlos Pérez García-Pando, Daven K. Henze, Oriol Jorba, Christoph A. Keller, Jason C. Knievel, Pius Lee, Paul Makar, Valéry Masson, Luca Delle Monache, Pablo Saide, Jose-Luis Santiago, Karine Sartelet, Mikhail Sofiev, William Stockwell, Daniel Tong, Shaocai Yu, Yang Zhang, Chunhong Zhou, and Sergej Zilitinkevich
- **Co-authors**: Dan Aliaga, Maria de Fatima Andrade, Sara Basart, Angela Benedetti, Marc Bocquet, Stefano Calmarini, Gregory Carmichael, Martin Cope, Arlindo da Silva, Hiep Duc, Georg Grell, Antje Inness, Lasse Johansson, Johannes W. Kaiser, Ari Karppinen, Zak Kipling, Alberto Martilli, Gerald Mills, Mariusz Pagowski, Gabi Pfister, Chao Ren, Glenn Rolph, Beatriz Sanchez, Adrian Sandu, and Ranjeet Sokhi.
- **Case providers**: A. Abdallah, Maria de Fatima Andrade, Charles Chemel, Odón R. Sánchez-Ccoyllo, Martin Cope, Anton Darmenov, Hiep Duc, Aidan R. Farrow Johannes Flemming, Edmilson Dias de Freitas, Jimmy Chi-Hung Fung, Christopher Gan, Christoph A. Keller, Kenza Khomsi, Youngseob Kim, Pius Lee, Kenneth Leung, Stuart McKeen, Mariusz Pagowski, Matthieu Plu, Chao Ren, Shital Rohekar, Karine Sartelet, Vikas Singh, Mikhail Sofiev, Ranjeet. S. Sokhi, Peter Yeung, Melaku Tesfaye Yigiletu, Shaocai Yu, Magdy M. Abdel Wahab, Yang Zhang, and Chunhong Zhou
- **Model description providers**: Maria de Fatima Andrade, Alexander Baklanov, Martin Cope, Hiep Duc, Johannes Flemming, Edmilson Dias de Freitas, Christopher Gan, Christoph Keller, Zak Kipling, Rostislav Kouznetsov, Pius Lee, Paul Makar, Karine Sartelet, Mikhail Sofiev, Ashraf Zakey, and Chunhong Zhou
- **Reviewers:** Véronique Bouchet, Frank Dentener, Sue Grimmond, Michaela Hegglin, Pablo Saide, Heinke Schluenzen, Ranjeet Sokhi, Jianguo Tan, Taichu Tanaka, and Chunhong Zhou

Characteristics of the Training Book

- **Describes basic principles, effective methods, and best practices important in the deployment and application of a 3D model for CW-AQF on different scales: from global to urban. It focuses only on 3D CW- AQF model, and it is not intended to be all-inclusive**
- **Summarize the current status, the state-of-the science CW-AQF models and their application and evaluation, special considerations for urban applications and extreme events, as well as advanced techniques for improved CW-AQF and uncertainty quantifications; Provides demonstration cases for representative regions in six major continents**
- **Provides practical recommendations for developing countries and urbanized regions how better to build a CW-AQF system on national, regional or city level**
- **Complement existing guidelines/reviews developed by governments/communities (e.g., 2003 guidelines by US EPA/NOAA/NWS; Zhang et al., 2012a,b, Kukkonen et al., 2012; Baklanov et al., 2015; Stajner et al., 2016; Ryan, 2016; Kumar et al., 2018)**

Outline of the CW-AQF Document

- Chapter 1. Introduction
- Chapter 2. History and Characteristics of CW-AQF
- Chapter 3. Fundamentals of CW-AQF
- Chapter 4. Model Deployment and Application
- Chapter 5. Special Considerations for Urban Applications
- Chapter 6. Special Considerations for Extreme Events
- Chapter 7. Model Input and Preparation
- Chapter 8. Model Output and Data Management
- Chapter 9. Model Evaluation
- Chapter 10. Bias Correction and Forecast Skill Improvement Methods
- Chapter 11. Uncertainty Quantification and Probabilistic Forecasting
- Chapter 12. Demonstration Cases for Real-Time CW-AQF
- Acknowledgements
- List of Tables
- List of Figures
- Nomenclature

Major Differences between Air Quality Backcasting and Forecasting

Attribute	Air Quality Backcasting	Air Quality Forecasting
Driving force	Regulatory guidance and compliance	Societal pressures to minimize the human, environmental and economic impacts
Input datasets	Best available historical dataset	Real-time or near-real time dataset
Format of input datasets	Pre-processed archived files	Automatic downloading and pre-processed RT or near RT dataset
Model mechanisms and treatments	Best available options	Simplified, optimized options to meet time requirements
Model option tuning and adjusting	Yes	No
Special techniques for accuracy and efficiency	None or rarely use	Bias correction, ensemble forecasting, data fusion
Typical application	Simulations of past high pollution events	Predictions of poor AQ days for public health notification and episodic control programs; planning air field studies
Products	Concentrations and deposition fluxes of chemical species	O_3, NO_2, $PM_{2.5}$, and PM_{10}, customized products, and post-calculated AQI and color codes
Time requirement for products	No time window requirements	Next-day's forecast must be available before 2 pm today
Evaluation of products	Temporal and spatial overlay; discrete statistical evaluation; uses the best available historic observational data	+ categorical evaluation; uses real-time or near real-time observational data
End users	Researchers, regulators, decision makers,	+ the public, the media, and the commercial sector
Goals and societal/economic benefits	Advancement in sciences, regulatory analyses and policy-making	Warnings for sensitive groups; actions to timely reduce exposure and emissions; cost-saving for large field campaigns
IT infrastructure	No special requirements	Web-based, interactive, and user-friendly interfaces

CW-AQF Numerical Model Systems and Applications in the U.S.

Model System	Met. Model	CTM	Forecasting Areas/Periods	AQF Products
NOAA/NWS NAQFC (Eta-CMAQ or WRF-CMAQ or FV3-CMAQ) modeling system	Eta or WRF (NMM) or FV3	Community Multiscale Air Quality (CMAQ) modeling system; SMOKE (off-line); in-line biogenics and mobile source emissions	E. U.S. (operational); CONUS (experimental); 12-km grid cells; 12 UTC – 48-hr run (next-day forecast)	O_3 (operational); $PM_{2.5}$ (developmental)
Baron Advanced Meteorological Systems (BAMS) MM5-MAQSIP/RT modeling system	NCAR/PSU MM5	Multiscale Air Quality Simulation Platform-Real Time (MAQSIP/RT); SMOKE (online)	CONUS – 45-km; Regional – 15-km; Metro-area – 5-km; 18 UTC – 120-hr run (next-day guidance)	O_3 and $PM_{2.5}$
NOAA/ESRL WRF/Chem	WRF (ARW)	Online coupled WRF/Chem; offline static anthro. emissions and online biogenic emissions	CONUS – 40-km; E. U.S. – 27-km; 00 UTC – 36-hr run: (next-day forecast)	O_3 and $PM_{2.5}$
NCSU WRF-Chem/MADRID	WRF (ARW)	Same as above except for WRF/Chem-MADRID	S.E. U.S. – 12-km; 00 UTC – 60-hr run: (next 2-day forecast)	O_3, $PM_{2.5}$, and PM_{10}

CW-AQF Numerical Model Systems and Applications Beyond U.S.

Model System	Met. Model	CTMs	Forecasting Areas/Periods	AQF Products
Australian AQF system	LAPS	Australian CTM; with static emissions inventory	Sydney and Melbourne; Nested domains with 1-5 km grid cells	O_3, urban aerosol, wind-blown dust, wildfire impacts
Germany EURAD modeling system	Univ. of Cologne MM5	European RADM model; with static emissions inventory	European continent domain with nested 125/25 km grid cells; 5 km over parts of Germany	O_3, CO, PM_{10}
French PREVAIR modeling system	Meteo France Ministry for Ecology MM5	CHIMERE or other models; with static emissions inventory	European continent with 0.5° grid cells; 0.1° over France	O_3, NO_x, $PM_{2.5}$, PM_{10}
Canadian GEM-CHRONOS modeling system, now online-coupled GEM-MACH	Meteorological Service of Canada (MSC) Global Environ. Model (GEM) Weather Forecasting model	Canadian Hemispheric and Regional O_3 and NO_x System (CHRONOS or MACH); SMOKE (off-line); in-line biogenics emissions	North American domain – 21-km; 00 UTC – 48-hr run: once per day forecast	O_3 and $PM_{2.5}$

See more Model examples in the WMO Training Materials for CW-AQF

AQF Products and Evaluations

- **CW-AQF Products**
  - O_3 (initial focus) and $PM_{2.5}$ (recent expansion)
  - CO, SO_2, NO, NO_2, VOCs, $PM_{2.5}$ composition, PM_{10}, and AOD
- **CW-AQF Lead Time**
  - 1-4 days for RT CW-AQF
  - 8-24 hrs for field study planning
- **CW-AQF Evaluation**
  - Most evaluations focus on O_3, fewer include its precursors
  - Limited evaluation of $PM_{2.5}$ AQF, fewer for coarse particles
  - Most evaluations focus on summer and very few include winter or full year

Evaluation of AQF Model Skills

Categorical Evaluation

- **Accuracy (A)**
  Percentage of forecasts that correctly predict an exceedance or a nonexceedance
- **Critical Success Index (CSI)**
  Indicate how well actual exceedances are predicted, accounting for both missed events and false alarms
- **Probability Of Detection (POD)**
  Percentage of actual exceedances that are forecasted, accounting for only missed events
- **Bias (B)**
  Judges if forecasts are underpredicted (< 1) or overpredicted (> 1)
- **False Alarm Ratio (FAR)**
  Measures the percentage of times an exceedance was forecasted when none occurred

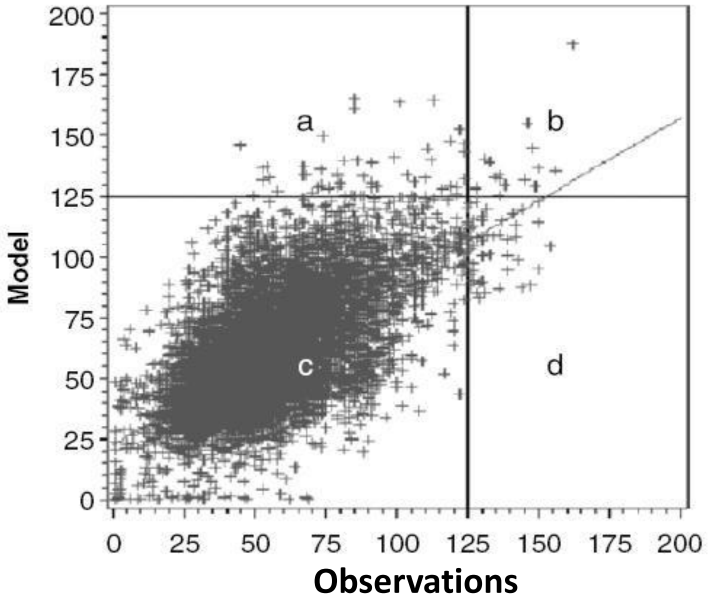
$$A = \left(\frac{b+c}{a+b+c+d}\right) \times 100\%$$

$$\mathrm{CSI} = \left(\frac{b}{a+b+d}\right) \times 100\%$$

$$\mathrm{POD} = \left(\frac{b}{b+d}\right) \times 100\%$$

$$B = \left(\frac{a+b}{b+d}\right)$$

$$\mathrm{FAR} = \left(\frac{a}{a+b}\right) \times 100\%$$



(Figure from Kang et al., 2005)

Scientific Advancements to Improve RT-AQF

- **Improvement of Meteorological Forecasts**
  - Representations of episodes that typically have very weak dynamical forcing (PBL schemes under strongly stable conditions and for nocturnal mixing layers)
  - Mesoscale circulations (e.g., land-sea breeze, topographic induced circulations, sea-breeze circulations, and their interactions with synoptic flows)
  - Meteorological forecasts at 1-km or smaller (stable/stagnation conditions, turbulence and vertical mixing, deep convection, low-level jets, land-surface processes, and precipitation)
- **Improvement of Chemical Inputs**
  - Initial and boundary conditions (outputs from a global CTM, assumed climatological profiles, and adaptation of satellite and surface data for chemical profiles)
  - Emissions (offline emissions; online emissions (e.g., mobile, biogenic, pollen, electric power generation, surface coating, wildfires, dust, sea-salt, and re-emissions))
- **Improvement of Physical, Dynamic, and Chemical Treatments**
  - Parameterizations of the urban environment (e.g., heterogeneity of building disposition, rough surface, anthropogenic heat fluxes the streets geometry)
  - Gas-phase chemistry representations (e.g., SAPRC2011/2007, CB05-TU, CB6)
  - Heterogeneous chemistry (e.g., HONO, reactions on sea-salt, photochemistry on soot)
  - Aerosol dynamics and chemistry (e.g., new particle formation and subsequent growth processes, SOA formation, mixing states)

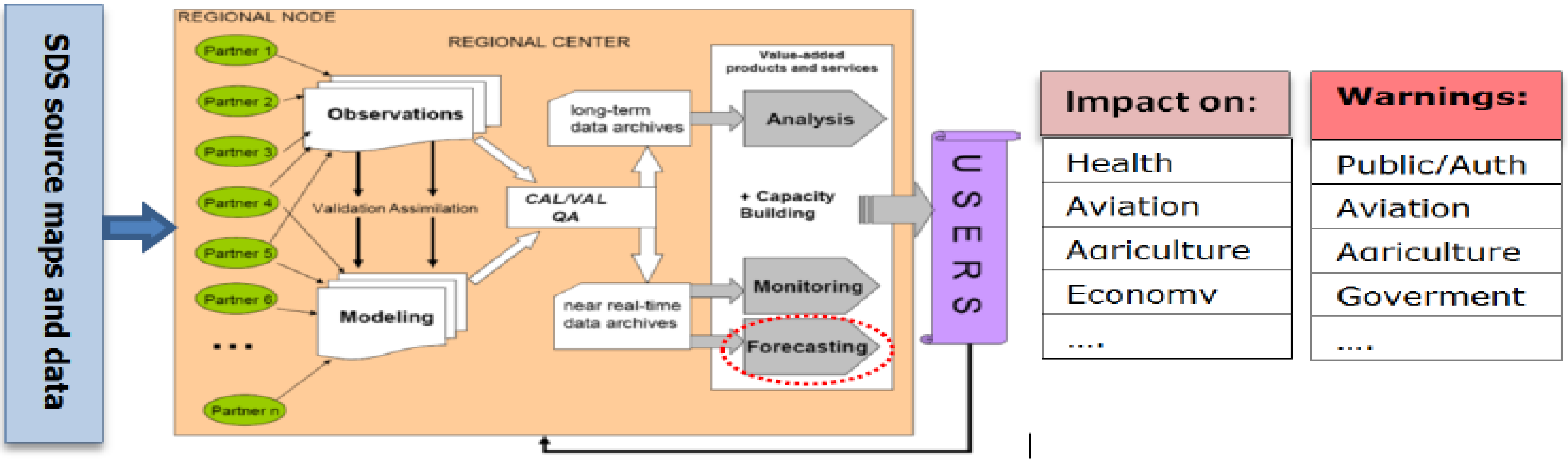
Numerical/Computational Techniques to Improve RT-AQF

- **Improvement in Initial Conditions (ICONs)**
- Simple approaches to improve model ICONs (e.g., the climatology of concentration profiles, satellite data with a broad spatial coverage)
- Advanced approches based on chemical data assimilation (e.g., 3DVAR, 4DVAR)
- Meteorological forecasts at 1-km or smaller (stable/stagnation conditions, turbulence, deep convection, low-level jets, land-surface processes, precipitation)

- **Improvement of Emissions, Boundary Conditions, or Model Parameters**
- Inverse modeling using data assimilation
- Multiscale data assimilation method
- **Ensemble Forecasting**
- Types (one model but with different inputs or multiple models)
- Methods (e.g., Monte Carlo simulations, multimodel ensembles, ensembles calibrated for uncertainty estimation, sequential aggregation, coupled sequential aggregation and classical data assimilation)
- **Other Types of Techniques**
- Simple bias correction methods
- Data fusion methods
- Combination of several bias-correction methods

Impact Based Forecast and Fit-for-Purposes Approach

- Example of impact-based forecast and assessment systems for the WMO Sand and Dust Storm Warning Advisory and Assessment System (SDS-WAS) (after Nickovic et al., 2015).



- Help stakeholders and responsible agencies to improve AQ and public health, mitigate occurrence of acute harmful AP episodes.

Major Challenges

Model Development and Improvement

- Improve Accuracy of Meteorological Forecasting
- Improve Representations of Urbanization
- Improve Representations of Other Atmos. Processes
- Develop/improve online-coupled met. and chem. models
- Apply Techniques for Accuracy Improvements
- Develop various bias correction approaches
- Improve/expand various CDA techniques to reduce uncertainty in inputs
- Develop ensemble forecasting to reduce error and estimate uncertainties
- Apply Techniques for Comp. Efficiency Improvements
- Develop efficient parameterizations/representations
- Optimize model schemes/algorithms and data interpolation algorithms
- Ensure a high level of automation and parallelism
- Use refinement techniques such as the dynamic adaptive grids techniques

Major Challenges:

Inputs, Outputs, and Community Outreach

- **Improve Accuracy of Model Inputs**
  - Develop better quantification of spatial/temporal emissions
  - Develop/improve online modules for weather-dependent emissions
  - Develop/improve methods for inversion modeling with data assimilation
  - Adapt observations to specify initial and boundary chemical profiles
  - Develop global-through-urban online-coupled models for ICs/BCs
- **Expand Model Outputs**
  - Include other pollutants (visibility/haze, air toxics, deposition)
  - Extend the lead time to 3-7 days
- **Promote Community/Stateholder Outreach and Increase of Awareness**
  - Develop consistent forecast guidance documents
  - Establish effective education and training programs
  - Develop and strengthen community outreach and public awareness programs
  - Support/coordinate centralized RT-AQF efforts region-, country-, and world-wide

Thank you!

WEATHER CLIMATE WATER
TEMPS CLIMAT EAU

WMO OMM

World Meteorological Organization
Organisation météorologique mondiale

List of Authors for Chapters 1-12 (51 authors from 15 countries)

#	Name	Affiliation	Country	email
1	Dan Aliaga	Purdue University	USA	Aliaga @cs.purdue.edu
2	Maria de Fatima Andrade	USP	Brazil	maria.andrade@iag.usp.br
3	Wyat Appel	EPA	USA	Appel.Wyat@epa.gov
4	Alexander Baklanov	WMO	Switzerland	Abaklanov@wmo.int
5	Sara Basart	BSC	Spain	sara.basart@bsc.es
6	Angela Benedetti	ECWMF	UK	Angela.Benedetti@ecmwf.int
7	Marc Bocquet	CEREA/ENPC	France	bocquet@cerea.enpc.fr
8	Gregory Carmichael	Uni of Iowa	USA	gcarmich@engineering.uiowa.edu
9	Oriol Jorba Casellas	BSC	Spain	oriol.jorba@bsc.es
10	Jason Ching	UNC-Chapel Hill	USA	jksching@gmail.com
11	Martin Cope	CSIRO	Australia	Martin.Cope@csiro.au
12	Arlindo Da Silva	NASA	USA	arlindo.dasilva@nasa.gov
13	Jose Luis Santiago Del Rio	CIEMAT	Spain	jl.santiago@ciemat.es
14	Hiep Duc	OEH/NSW	Australia	Hiep.Duc@environment.nsw.gov.au
15	Johannes Flemming	ECMWF	UK	johannes.flemming@ecmwf.int
16	Edmilson Freitas	USP	Brazil	edmilson.freitas@iag.usp.br
17	Carlos Pérez García-Pando	BSC	Spain	carlos.perez@bsc.es

List of Authors for Chapters 1-12 (51 authors from 15 countries)

#	Name	Affiliation	Country	email
18	Stefano Galmarini	JRC	EU	stefano.galmarini@jrc.ec.europa.eu
19	Daven Henze	Uni of Colorado	USA	Daven.Henze@colorado.edu
20	Antje Inness	ECMWF	UK	a.inness@ecmwf.int
21	Johannes Kaiser	MPIC	German	j.kaiser@mpic.de
22	Ari Karppinen	FMI	Finland	Ari.Karppinen@fmi.fi
23	Christoph Keller	NASA	USA	christoph.a.keller@nasa.gov
24	Zak Kipling	ECMWF	UK	zak.kipling@ecmwf.int
25	Jason Knievel	NCAR	USA	knievel@ucar.edu
26	Lasse Johansson	FMI	Finland	Lasse.Johansson@fmi.fi
27	Pius Lee	NOAA	USA	pius.lee@noaa.gov
28	Paul Makar	Environ Canada	Canada	paul.makar@canada.ca
29	Alberto Martilli	CIEMAT	Spain	alberto.martilli@ciemat.es
30	Valéry Masson	Meteo-France	France	Valery.masson@meteo.fr
31	Volker Matthias	HZG	German	volker.matthias@hzg.de
32	Gerald Mills	UCD	Ireland	gerald.mills@ucd.ie
33	Luca Delle Monache	NCAR	USA	lucadm@ucar.edu
34	Mariusz Pagowski	NOAA	USA	mariusz.pagowski@noaa.gov

List of Authors for Chapters 1-12 (51 authors from 15 countries)

#	Name	Affiliation	Country	email
35	Gabi Pfister	NCAR	USA	pfister@ucar.edu
36	Chao Ren	CUHK	China	renchao@cuhk.edu.hk
37	Glenn Rolph	NOAA	USA	glenn.rolph@noaa.gov
38	Pablo Saide	UCLA	USA	saide@atmos.ucla.edu
39	Odón R. Sánchez-Ccoyllo	Universidad Nacional Tecnológica de Lima Sur (UNTELS)	Peru	osanchezbr@gmail.com
40	Beatriz Sanchez	CIEMAT	Spain	Beatriz.Sanchez@ciemat.es
41	Adrian Sandu	Virginia Tech	USA	asandu7@vt.edu
42	Karine Sartelet	CEREA/ENPC	France	karine.sartelet@enpc.fr
43	Mikhail Sofiev	FMI	Finland	Mikhail.Sofiev@fmi.fi
44	Ranjeet Sokhi	University of Hertfordshire	UK	r.s.sokhi@herts.ac.uk
45	William Stockwell	DRI/UTEP	USA	william.r.stockwell@gmail.com
46	Daniel Tong	NOAA	USA	daniel.tong@noaa.gov
47	Melaku Tesfaye Yigiletu	SAWS	South Africa	Melaku.Yigiletu@weathersa.co.za
48	Shaocai Yu	Zhejiang Uni	China	shaocaiyu@zju.edu.cn
49	Chunhong Zhou	CMA	China	Zhouch@cma.gov.cn
50	Sergej Zilitinkevich	FMI	Finland	Sergej.zilitinkevich@fmi.fi
51	Yang Zhang	NCSU	USA	yzhang9@ncsu.edu

References

- GAW IP, 2017, WMO Global Atmosphere Watch (GAW) Implementation Plan: 2016-2023. https://library.wmo.int/doc_num.php?explnum_id=3395
- Zhang, Y. and A. Baklanov (Editors), 2019, *Best Practices and Training Materials for Chemical Weather/Air Quality Forecasting (CW-AQF)*, pp 560, The first (draft) edition is available on: https://elioscloud.wmo.int/share/s/WB9UoQ5kQK-dmgERjSAqIA.
- Zhang, Y., C. Seigneur, M. Bocquet, V. Mallet, and A. Baklanov, 2012, Real-Time Air Quality Forecasting, Part I: History, Techniques, and Current Status, *Atmospheric Environment*, 60, 632-655, doi:10.1016/j.atmosenv.2012.06.031.
- Zhang, Y., C. Seigneur, M. Bocquet, V. Mallet, and A. Baklanov, 2012, Real-Time Air Quality Forecasting, Part II: State of the Science, Current Research Needs, and Future Prospects, *Atmospheric Environment*, 60, 656-676, doi:10.1016/j.atmosenv.2012.02.041.
- Baklanov, A., V. Bouchet, B. Vogel, V. Marécal, A. Benedetti, K. H. Schlünzen, 2015, Seamless Meteorology-Composition Models (SMCM): Challenges, gaps, needs and future directions. Chapter 12 in the WWOSC Book: Seamless Prediction of the Earth System: from Minutes to Months, (G Brunet, S Jones, PM Ruti Eds.), (WMO-No. 1156), (ISBN 978-92-63-11156-2), Geneva, pp. 213-233, 2015
- Kukkonen, J., Olsson, T., Schultz, D. M., Baklanov, A., Klein, T., Miranda, A. I., Monteiro, A., Hirtl, M., Tarvainen, V., Boy, M., Peuch, V.-H., Poupkou, A., Kioutsioukis, I., Finardi, S., Sofiev, M., Sokhi, R., Lehtinen, K. E. J., Karatzas, K., San José, R., Astitha, M., Kallos, G., Schaap, M., Reimer, E., Jakobs, H., and Eben, K., 2012, A review of operational, regional-scale, chemical weather forecasting models in Europe, *Atmos. Chem. Phys.*, 12, 1–87, https://doi.org/10.5194/acp-12-1-2012
- Kumar, R., V.-H. Peuch, J.H. Crawford, G. Brasseur, 2018, Five steps to improve air-quality forecasts. *Nature*, 6 September 2018, 561: 27-29.