Possible feedbacks of aerosols on meteorology

2nd lecture: *Model realization examples*

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(Based on results of EGU-2011 COST7 ES1004 'Online Modelling' Section, and model studies by U. Korsholm, G. Grell, G. Carmichael, Y. Zang and J. Flemming)

MUSCATEN summer school

"Integrated Modelling of Meteorological and Chemical Transport Processes / Impact of Chemical Weather on Numerical Weather Prediction and Climate Modelling"

Odessa, Ukraine, 3-9 July 2011

Lecture's Objective and Goal:

- **Description of the main feedback mechanisms of the chemical weather (atmospheric green-house gases and aerosols) impact on NWP and climate processes, in order to understand how important it is to include feedbacks from gases, aerosols, clouds, etc. in NWP, CWF and climate models.**
- **The goal is to give an orientation/understanding of which feedback processes are the most important: impact of feedbacks from gases, aerosols (direct, semi-direct, indirect effects), clouds, etc. on short and long time-range meteorological models.**
- **This subject is the main focus of the school. First part (1st lecture) focuses on the physical processes behind these feedbacks. Second part (2nd lecture) focuses on model examples.**

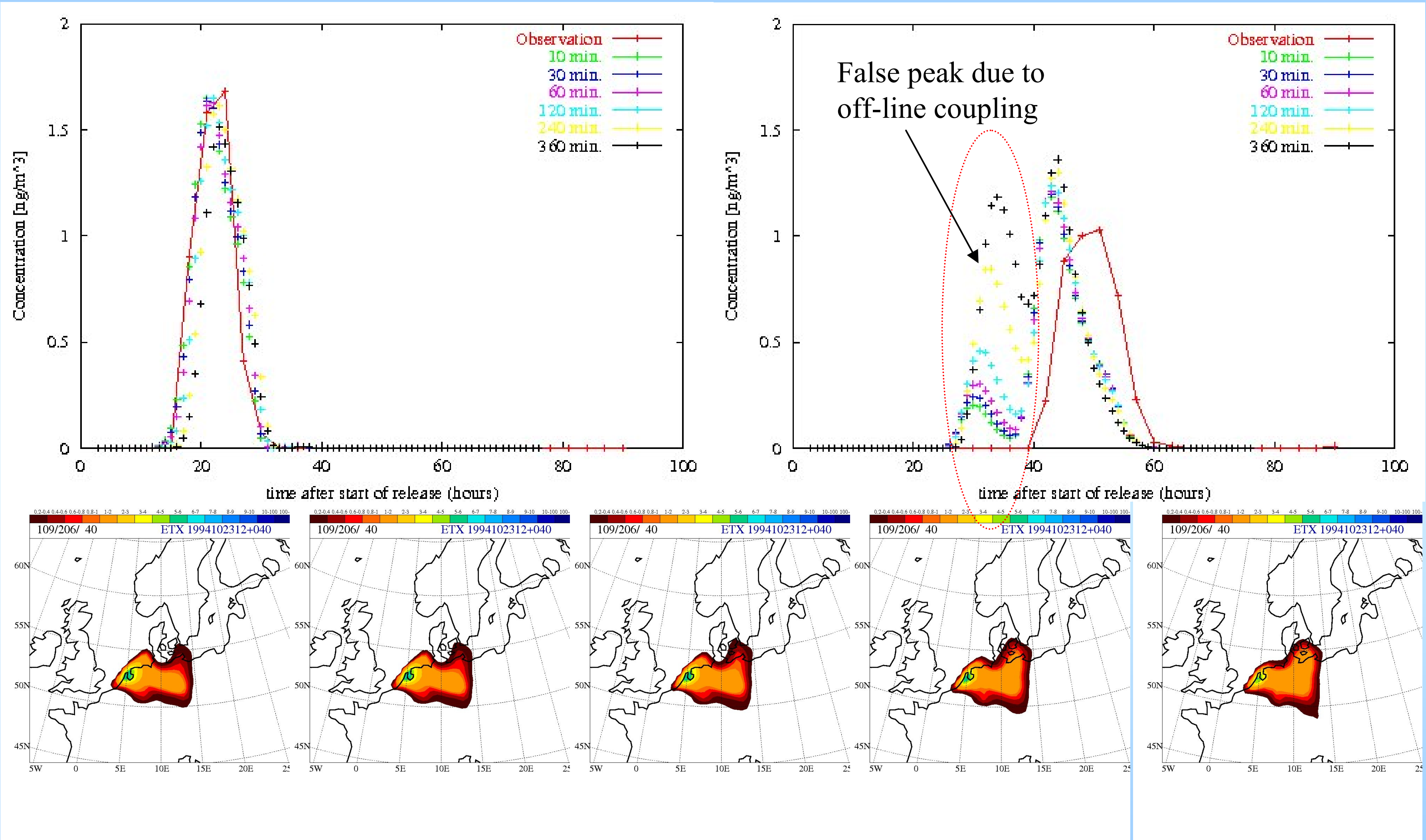
Feedbacks of aerosols on meteorology and atmospheric pollution

- Online models: Enviro-HIRLAM, WRF-Chem, C-IFS
- Aerosol feedbacks included
- *Will this make a difference for weather forecasts?*
- *Will this make a difference for air quality forecasts?*
- *Will this make a difference for urban climate?*

ENVIRO-HIRLAM

By DMI team: Korsholm et al.

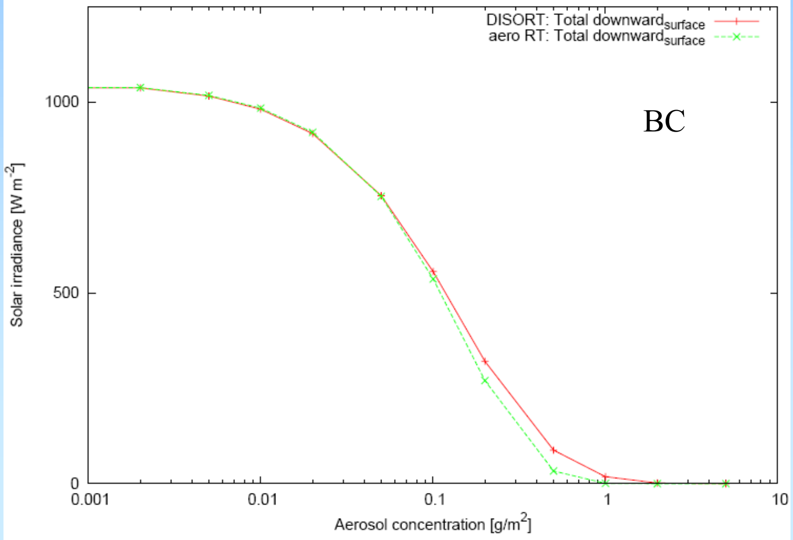
ETEX: Enviro-HIRLAM On-line/Off-line Validation



Top: concentration as function of time at F15 and DK02 for different coupling intervals: 30, 60, 120, 240, 360 minutes. Bottom: concentration after 36 hours with the same coupling intervals

Korsholm et al., AE, 2009

Aerosol direct effect



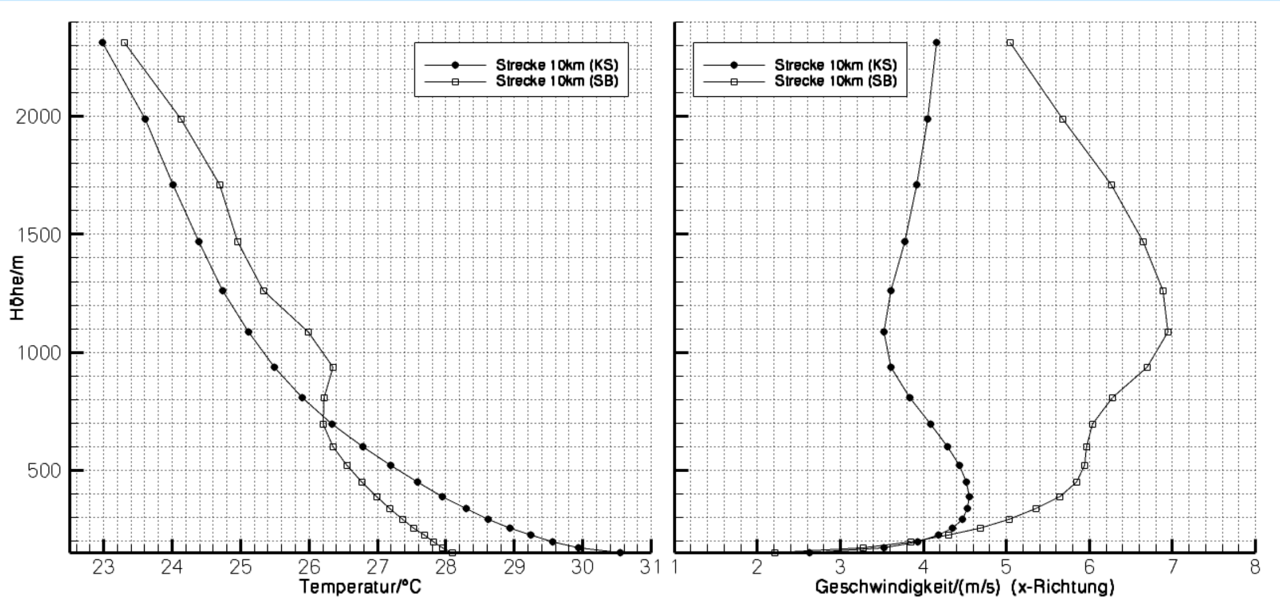
Direct aerosol effects on SW radiation was run in detail for the aerosol species in GADS (1997) by the DISORT model, considering the full spectral radiance field.
The species include BC (soot), Minerals (nucleus mode, acc. mode, coarse mode and transported mode), Sulphuric acid, Sea salt (acc. mode and coarse mode), "water soluble", and "water insoluble“

Courtesy of DMI: Nielsen et al

Urban aerosol direct effect

Comparison of temperature and wind speed profiles calculated for the continental clean (KS) and urban polluted (SB) aerosol types at the centre of the computational domain (elevations are above sea level)
Left picture: temperature profiles
Right picture: profiles of wind speed component parallel to the longitudinal direction

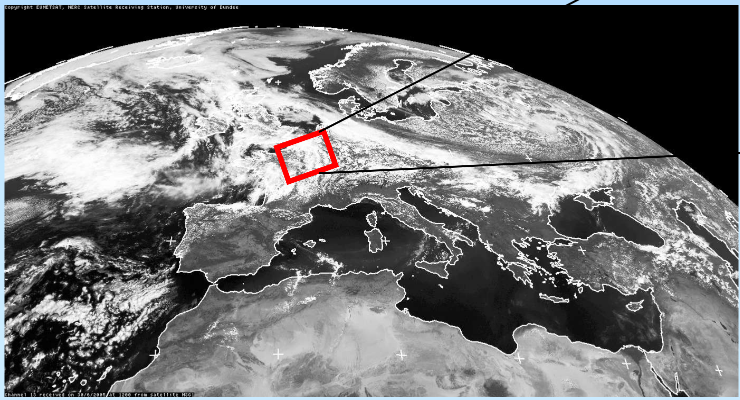
Courtesy of AUTH: Moussiopoulos et al

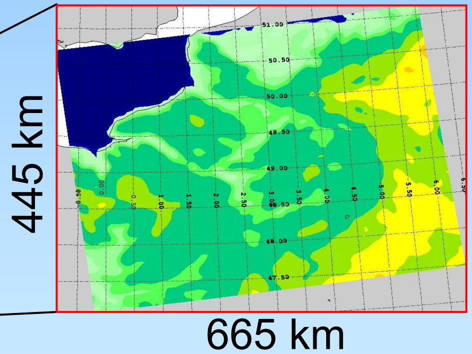


Enviro-HIRLAM: Indirect Aerosols Feedbacks

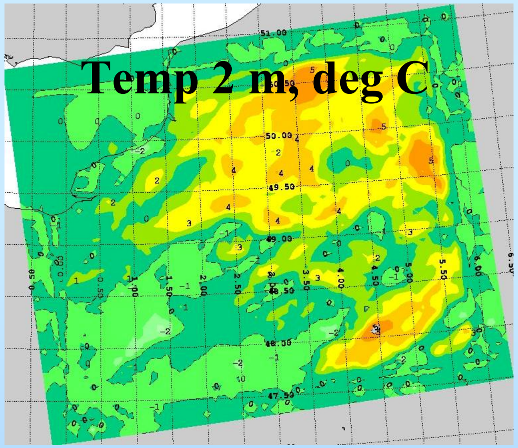
Paris Case Study:
28 Jun – 3 Jul 2005

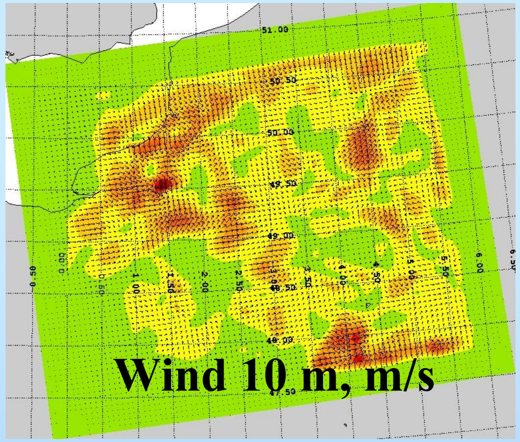
(Korsholm et al., 2009)

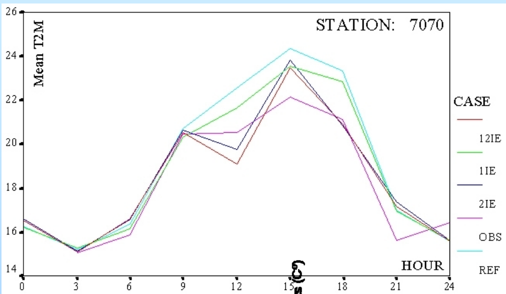


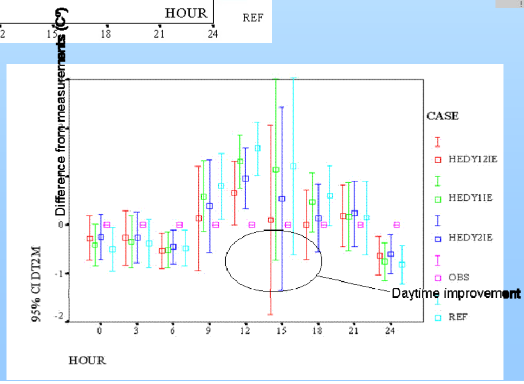


Difference (reference - perturbation)









Changes in:

- temperature – up to 2-3 (mon. av. 0,5) deg C,
- wind speed – up to 2-4 m/s,
- urban boundary layer height – up to 200 m,
- dry and wet deposition – up to 7%.

Findings

In this particular meteorological case: 2IE led to a general better T_{2m} comparison during Daytime; only small changes during night,
1IE was small in comparison (larger for thin clouds),
urban parameterization had negligible effect (strong large scale forcing).

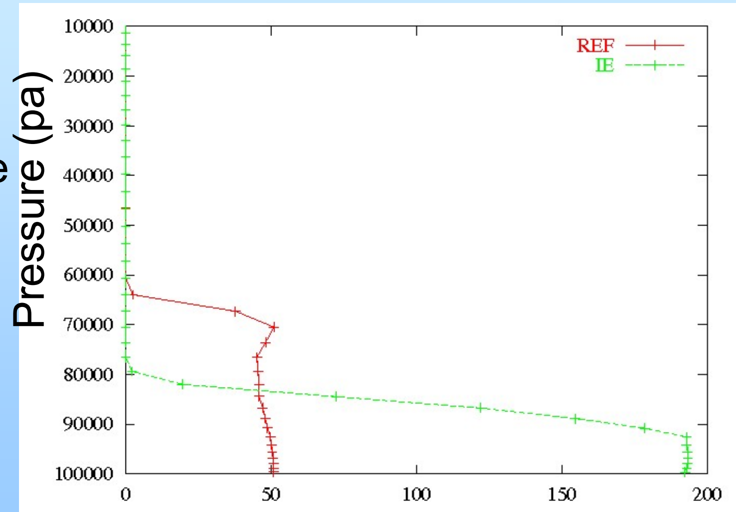
Dominating process in this case:

Paris → Aerosols → Increased Cloud cover (2[nd] aerosol indirect effect)

→ Shortwave, long wave response → Daytime cooling, night time heating

Additionally: local thermally induced circulations redistribute the aerosols and trace gases:

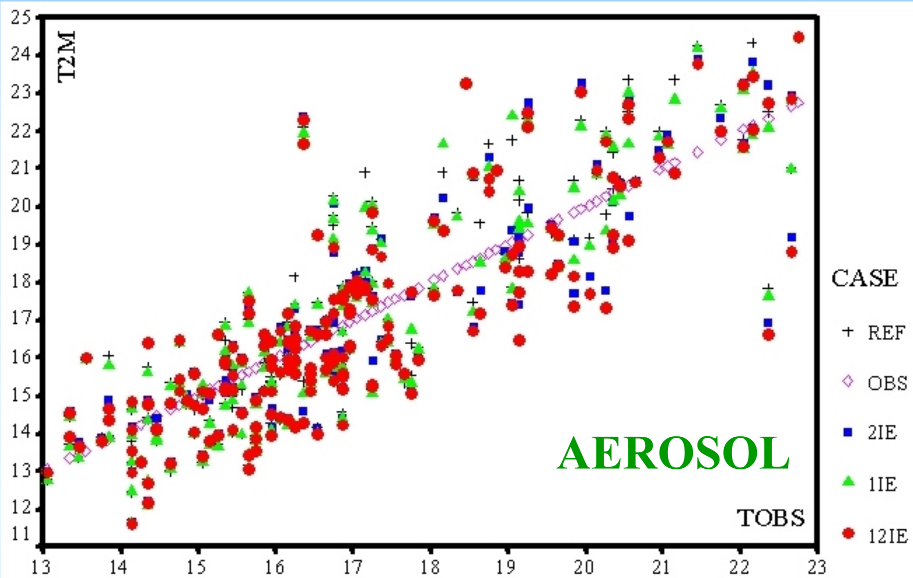
Vertical NO_2 profile in point of max. increase (49.2N;2.7E) during daytime 2005-06-29 at 12 UTC for the REF simulation (red) and the simulation including the indirect effects (green)

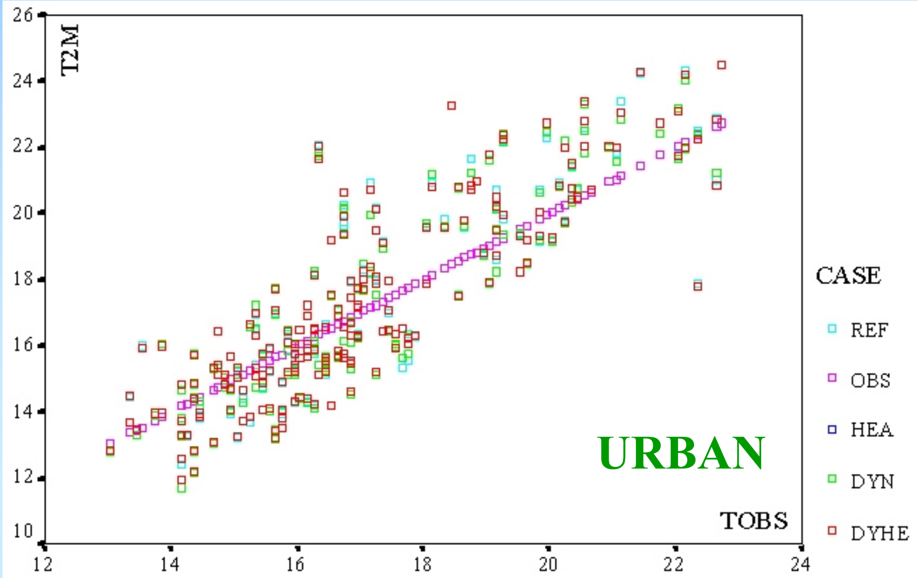


concentration (µg m^{-3})

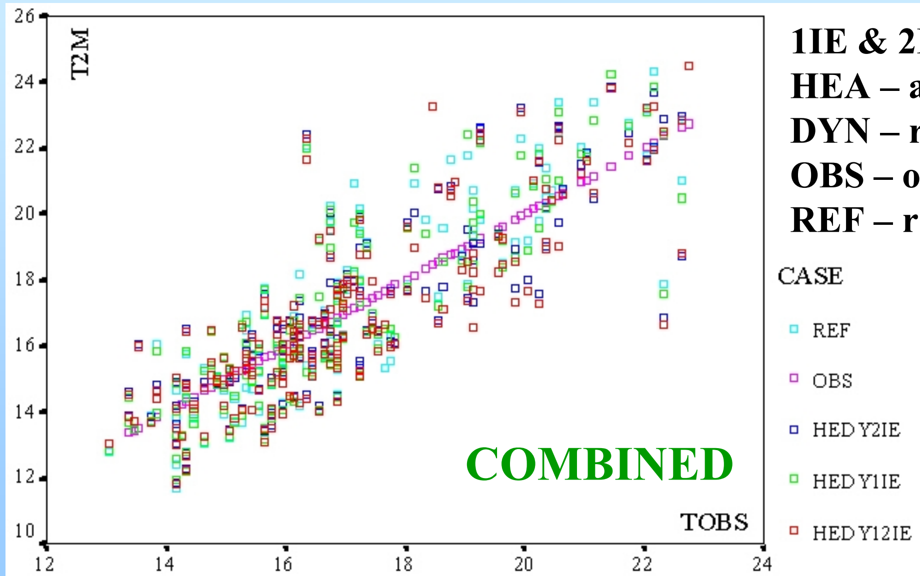
Korsholm et al., 2009

Paris Runs – Aerosol vs. Urban Effects - 1





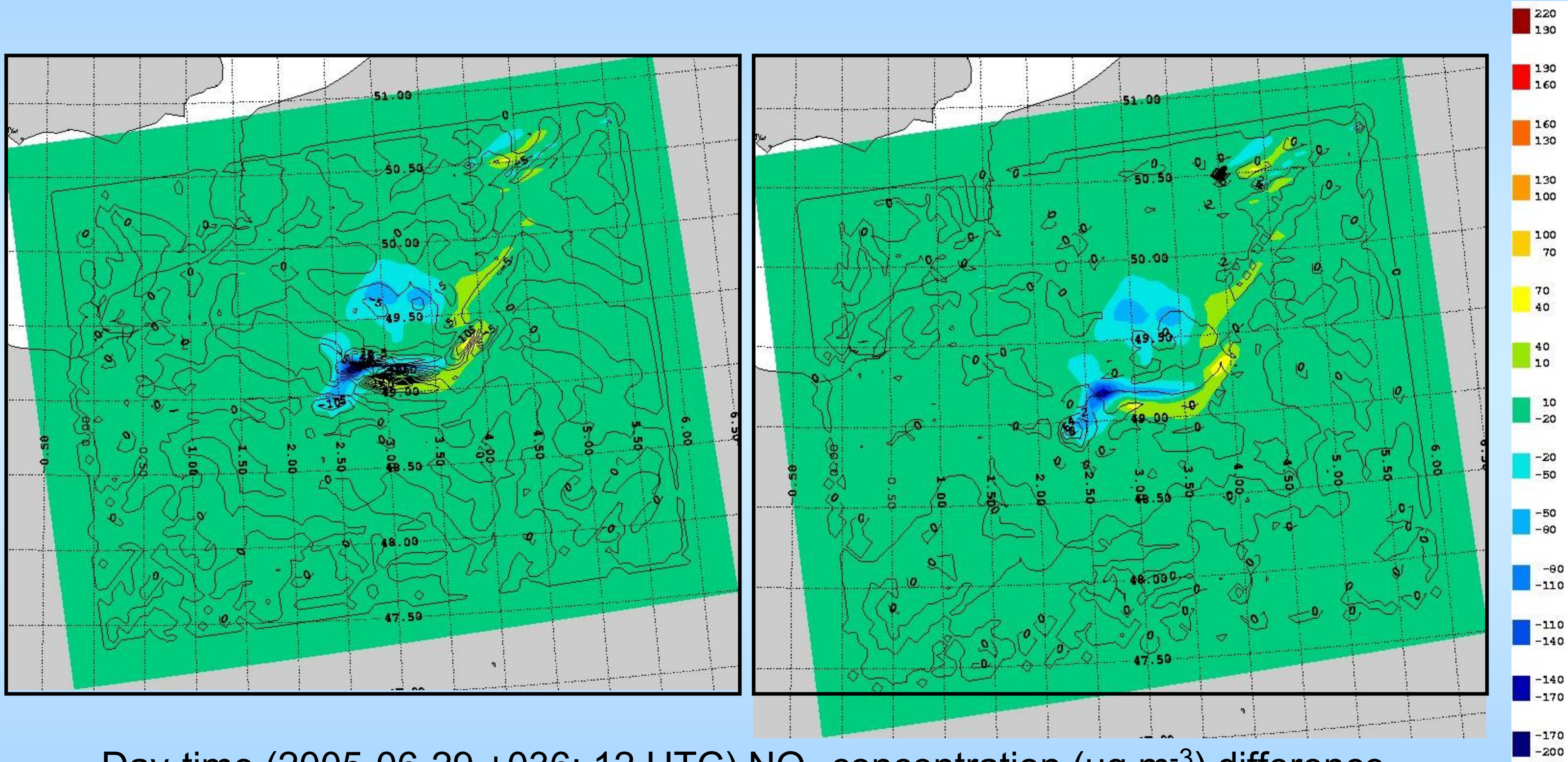
Parameter	Global Cor
DYN	0,856
HEA	0,857
DYN+HEA	0,857
2IE	0,831
1IE	0,852
12IE	0,821
DYN+HEA+1IE	0,855
DYN+HEA+2IE	0,829
DYN+HEA+1IE+2IE	0,820
REF	**0,855**



1IE & 2IE – 1st & 2nd indirect effects
HEA – anthropogenic heat flux
DYN – roughness
OBS – observations
REF – reference run / non-modified

Korsholm et al., 2009

Results: Meteorology vs. chemistry



Day-time (2005-06-29 +036; 12 UTC) NO_2 concentration (µg m^{-3}) difference (reference-perturbation) with dynamical (right) and chemical (left) tendencies (µg m^{-3} s^{-1}) overlain.

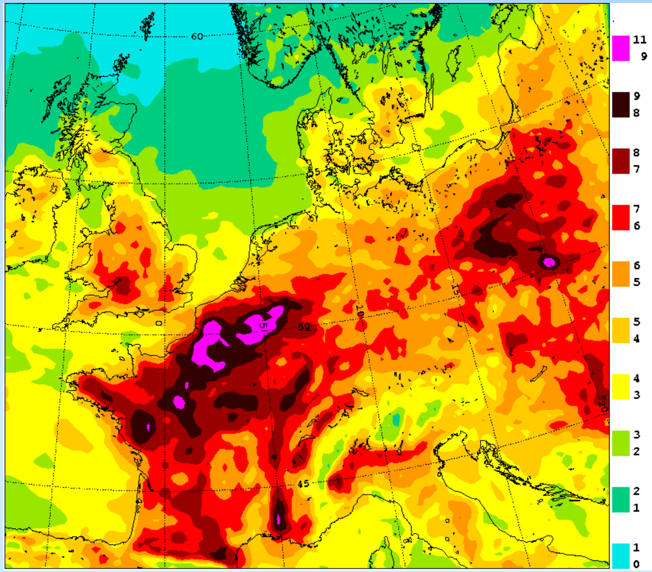
Korsholm et al., 2009

Indirect effects: conclusions

In this particular case (Korsholm et al., 2009):

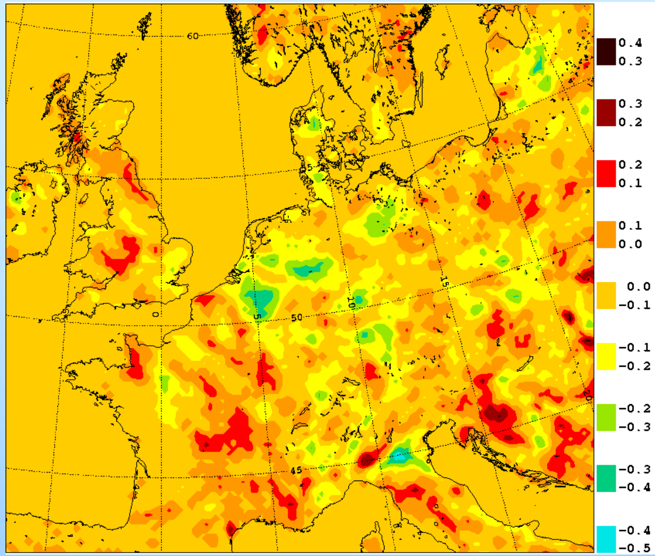
- **Indirect aerosol effects induce large changes in NO_2**
- **Changes mediated through changes in dynamcis**
- **Residual circulation induced by temperature changes**
- **Redistribution both vertically and horizontally**
- **Also applies for night-time conditions**
- **Chemistry vs dynamics**
- **Fist indirect effect is much smaller than second one**
- **Large non-linear component**
- **Monthly averaged signal in surface temperature of about 0.5 °C**

MEGAPOLI study: Comparing simulations with and without aerosol indirect effects for June 2009

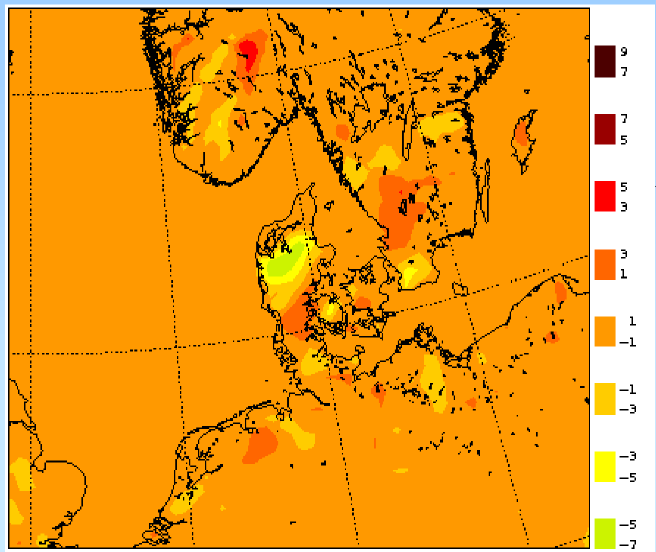


Monthly averaged CCN number concentration (x10^7 m^{-3}) at 850 hPa.

Monthly averaged difference in T_s (°C) (RUN - BASELINE)

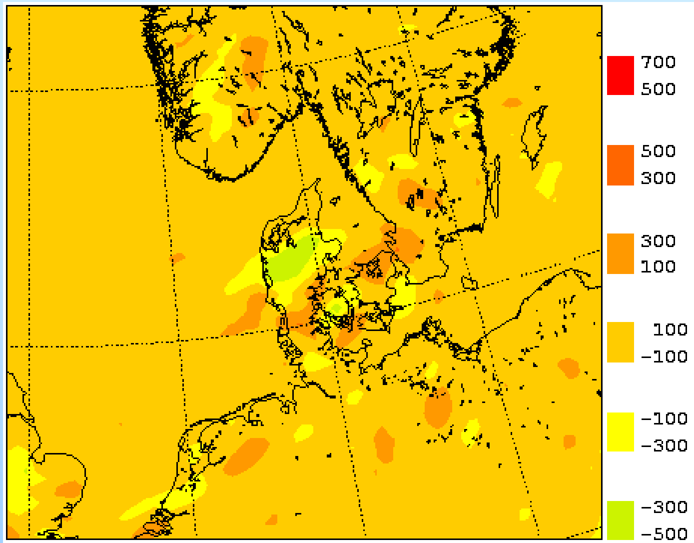


Korsholm et al., 2010



Change in T_s (°C) over Denmark on 8 June 2009 at 12 UTC (RUN - BASELINE)

Change in net SW radiation at the surface ($W\ m^{-2}$) on 8 June 2009 at 12 UTC (RUN - BASELINE)



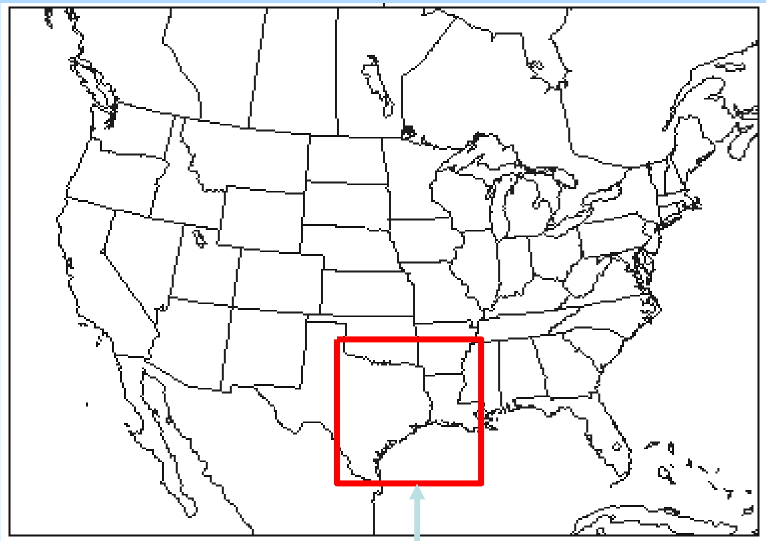
Korsholm et al., 2010

WRF/Chem-MADRID for USA

By Yang Zhang (NCSU)

WRF/Chem-MADRID model Study *(Y. Zang, 2007)*
Model Configurations

July 1-7 2001 CONUS



- Horizontal resolution: 36 km (148 × 112)
- Vertical resolution:
  - MM5 (L34), CMAQ (L14)
  - WRF/Chem (L34)
- Emissions:
  - SMOKE: US EPA NEI'99 (v3)
- Initial and boundary conditions:
  - The same ICs/BCs for WRF/ MM5 and for CMAQ and WRF/Chem
- Gas-phase chemical mechanism:
  - CMAQ: CB05
  - WRF/Chem: CB05 or CBMZ
- Data for model evaluation:
  - CASTNet and SEARCH

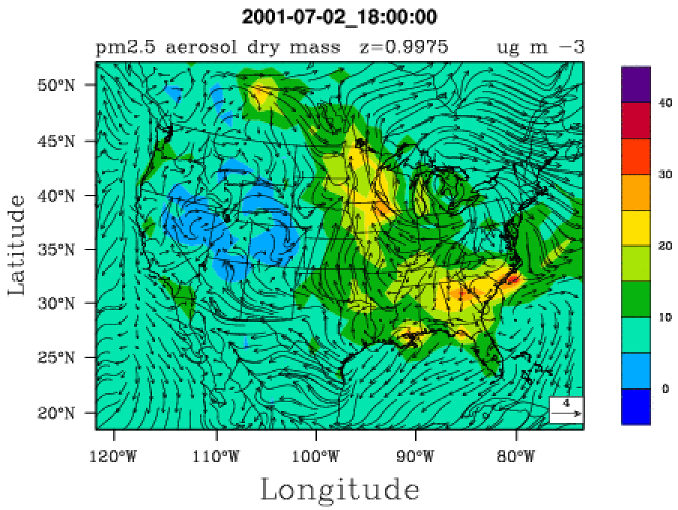
Aug. 28-Sept. 2, 2000 TeXAQS

- Horizontal resolution: 12 km (88 × 88)
- Vertical grid spacing: L57, 15-m at L1
- Emissions
  - Gases from TCEQ
  - PM based on EPA's NEI'99 V. 3 + online s.s.
- Initial/boundary conditions
  - 3-hr N. Amer. reg. reanal. for met.
  - Horizontally homogeneous ICs
- Gas-phase chemical mechanism: CBMZ
- Data for model evaluation
  - CASTNet, IMPROVE, AIRS, STN, TeXAQS

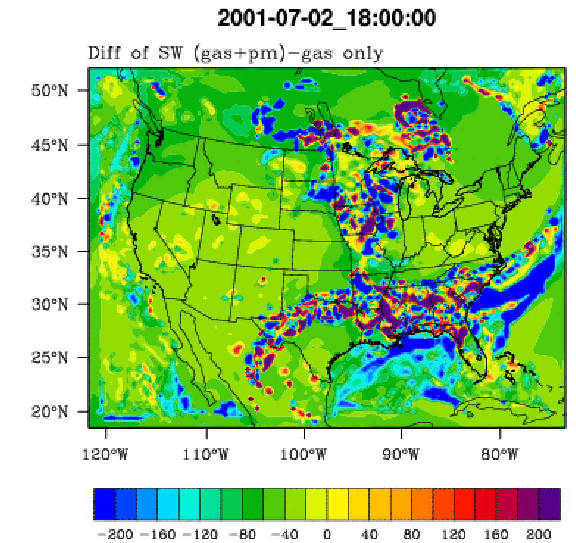
WRF/Chem-MADRID-CBMZ

Effects of Aerosols on Meteorology and Radiation

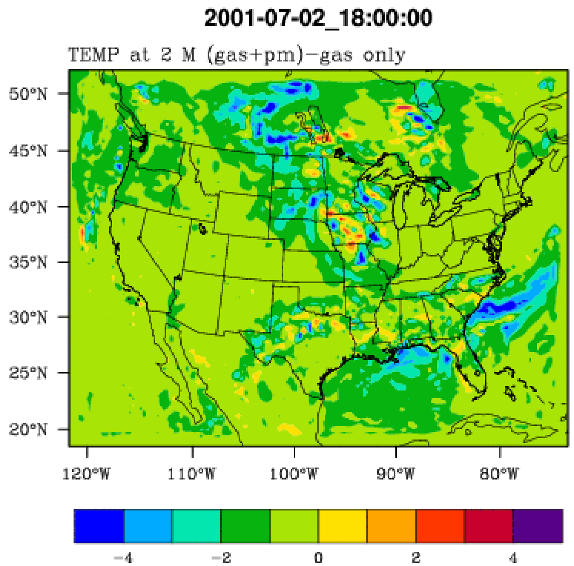
PM2.5



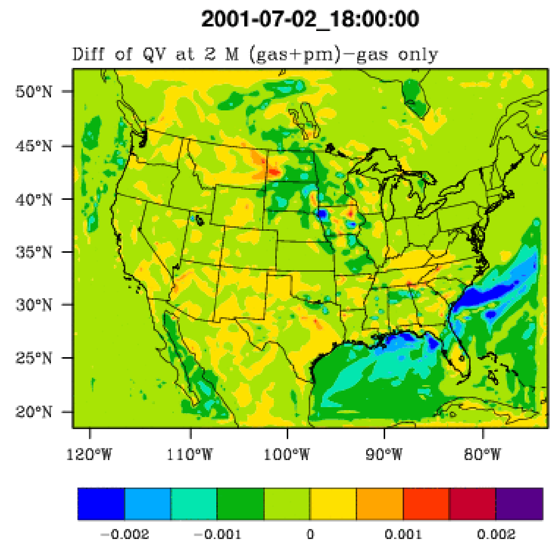
SW Radiation (-20 to 20%)



2-m Temp (-20% to 10%)



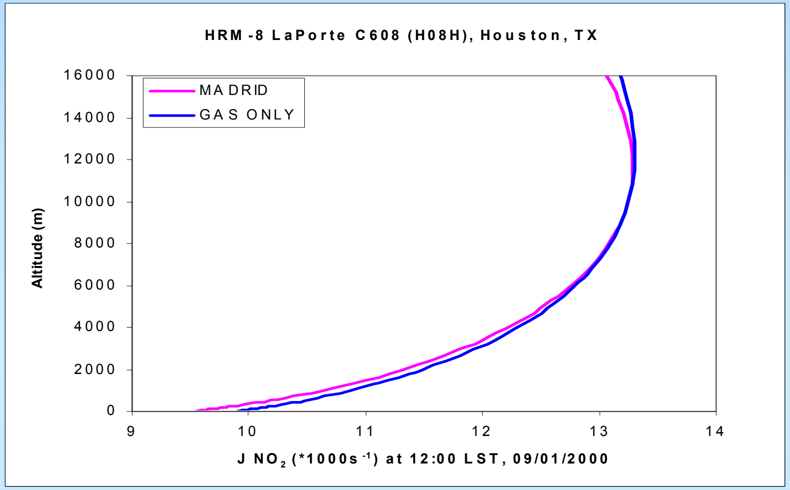
2-m Water Vapor (-10% to 10%)



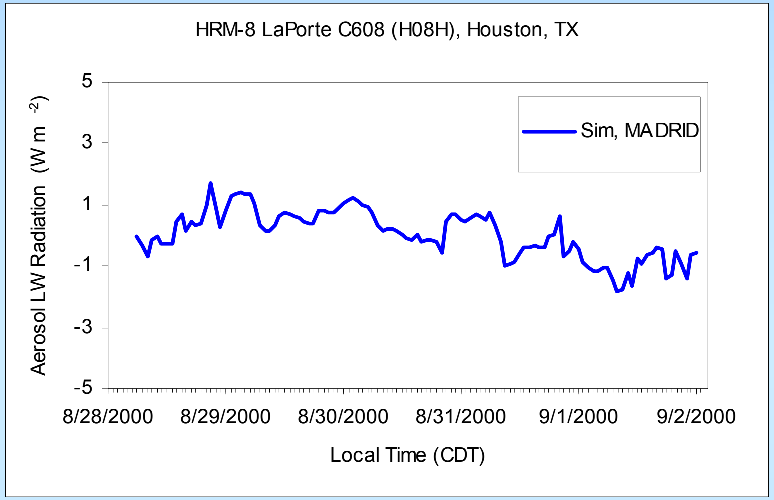
WRF/Chem-MADRID-CBMZ

Feedbacks of Aerosols to NO_2 Photolysis and Radiation

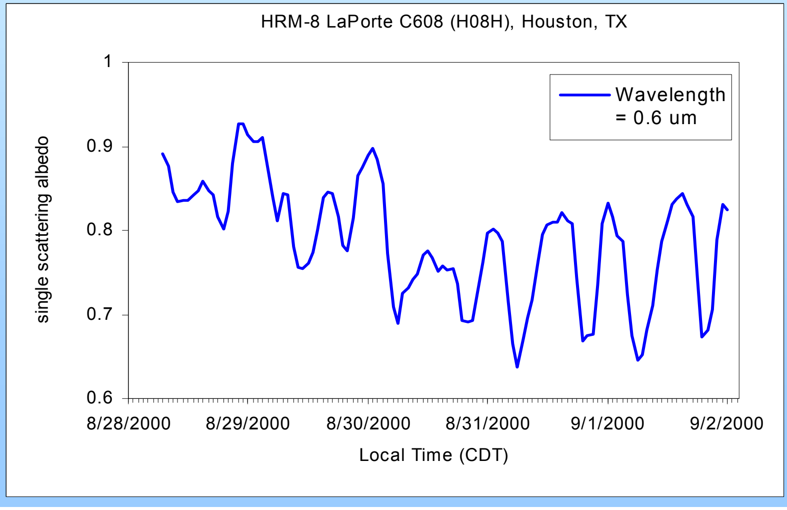
NO_2 Photolysis



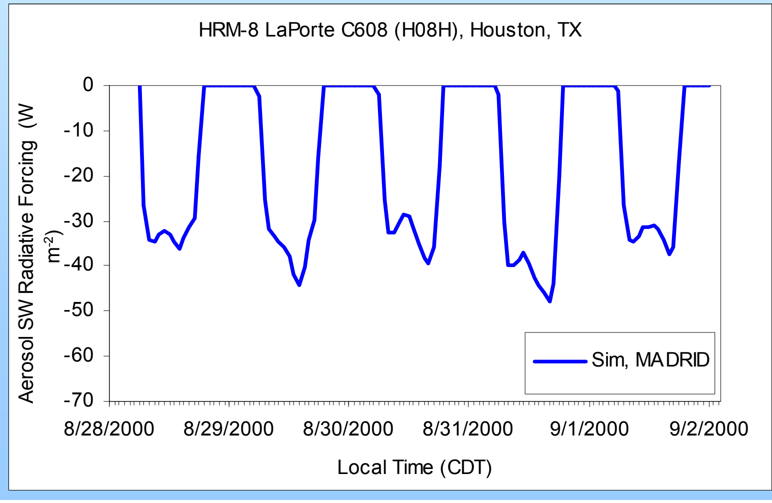
LW Radiative Forcing



Single Scattering Albedo

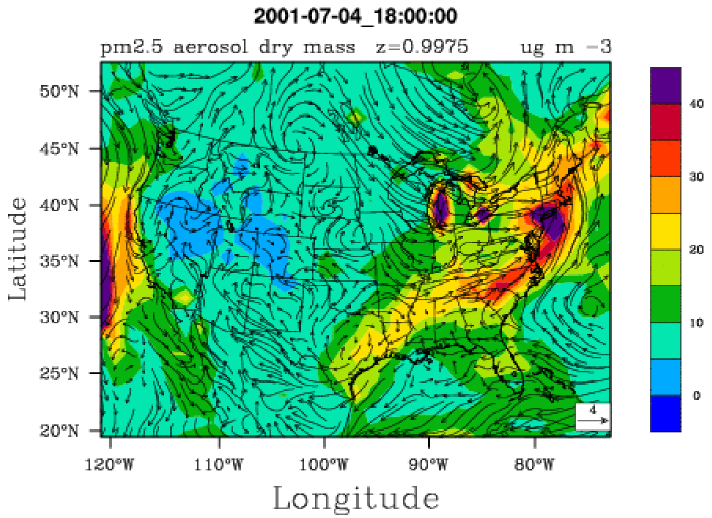


SW Radiative Forcing

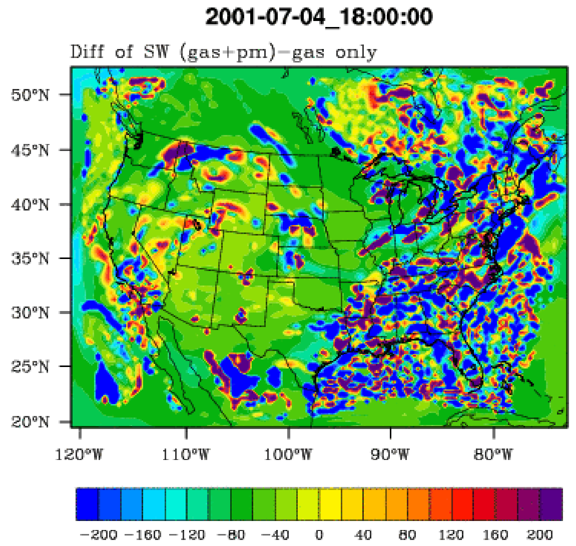


WRF/Chem-MADRID-CBMZ (old):
Effects of Aerosols on Meteorology and Radiation

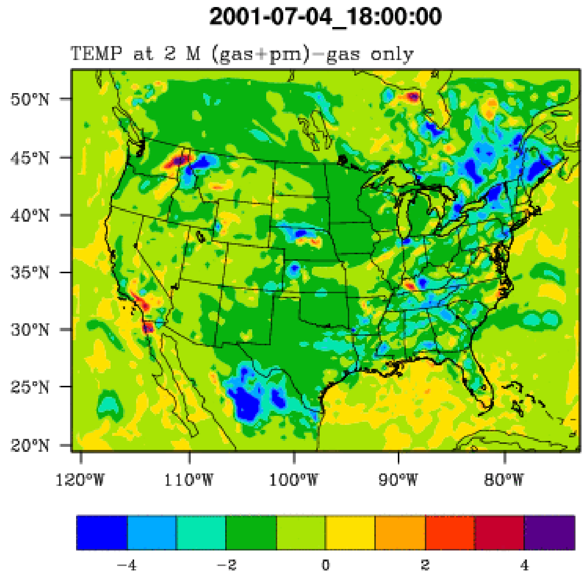
PM2.5



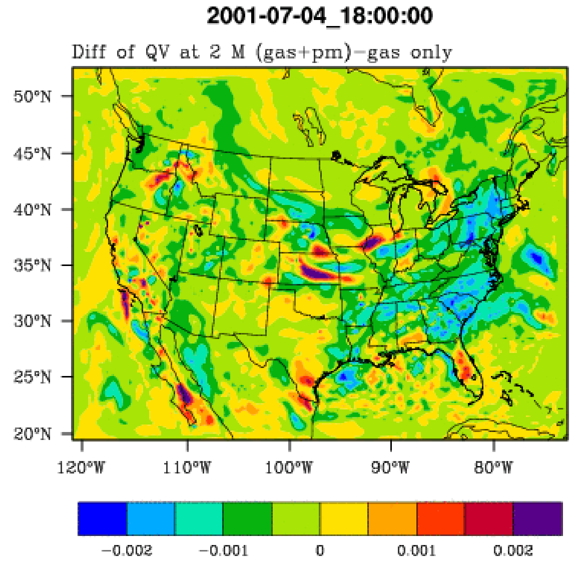
SW Radiation (-20 to 20%)



2-m Temp (up to -2%)



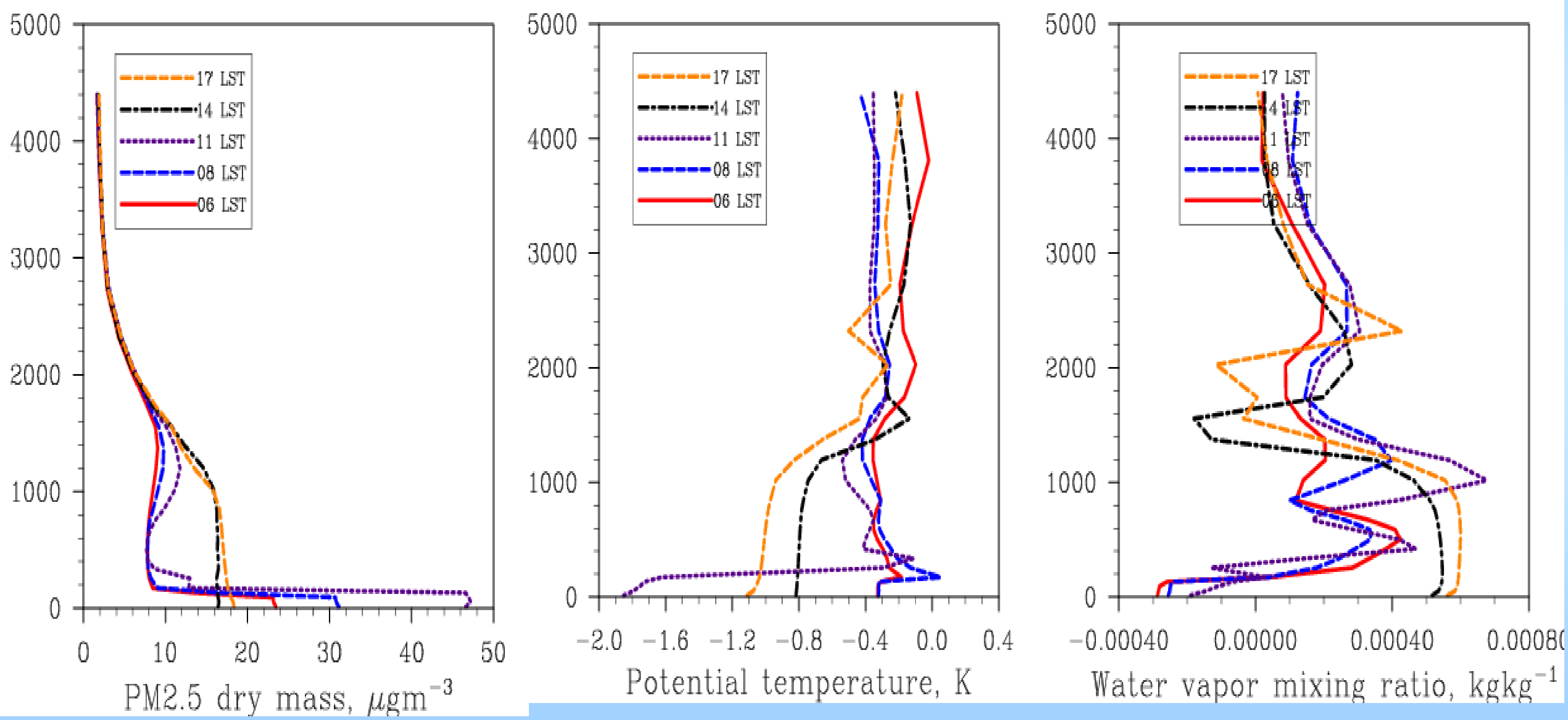
Water Vapor (up to -15%)



WRF/Chem-MADRID-CBMZ

Feedbacks of Aerosols to T and Q_v at Houston, TX

$PM_{2.5}$ **(Gas+PM - Gas only)**



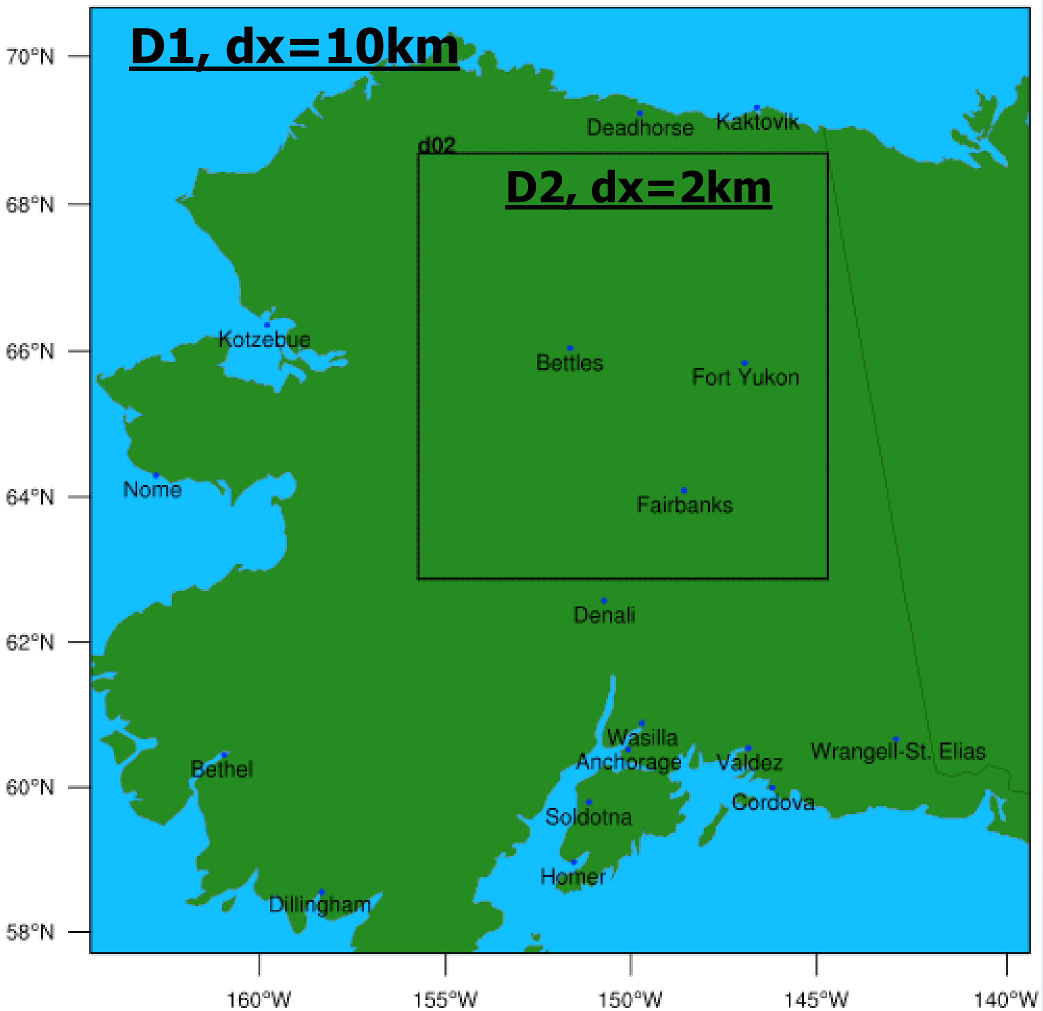
Diff > 0, T(Qv) increases (decreases) due to aerosol feedbacks
Diff < 0, T(Qv) decreases (increases) due to aerosol feedbacks

WRF-Chem for Alaska

By Georg Grell (NOAA)

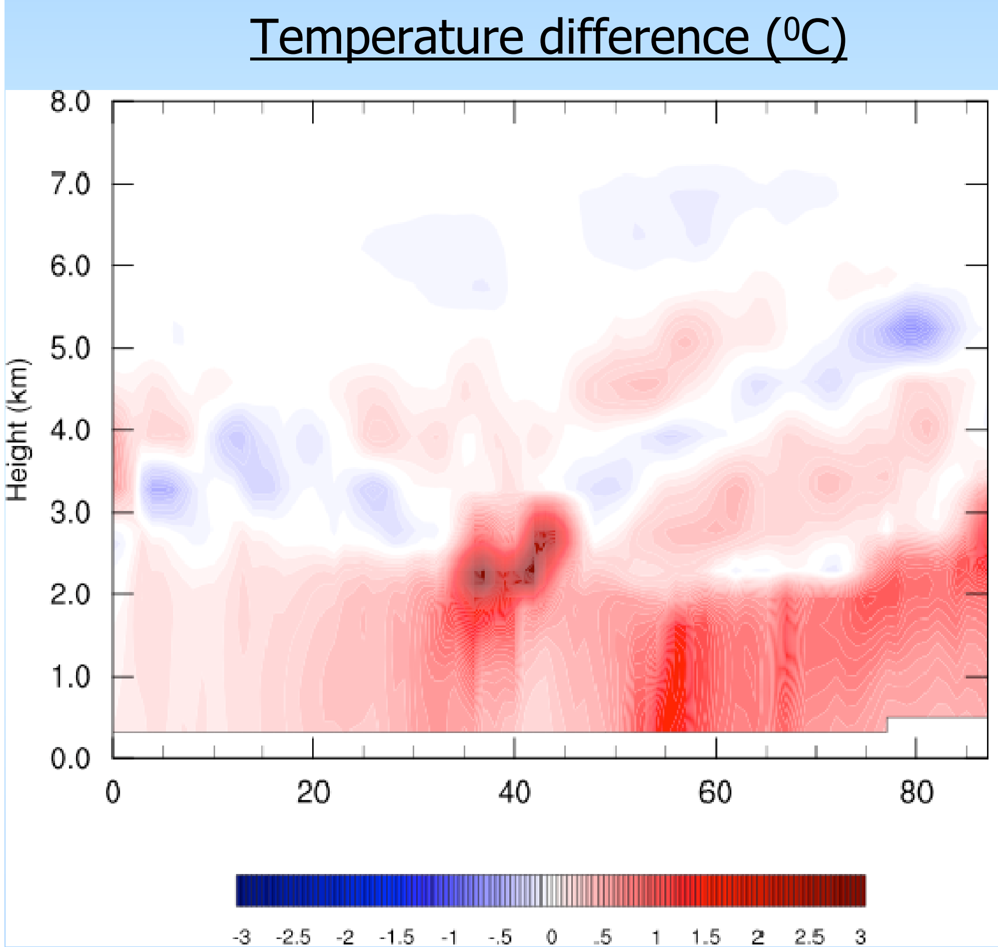
WRF-Chem Study for Alaska forest fires by G. Grell (NOAA)

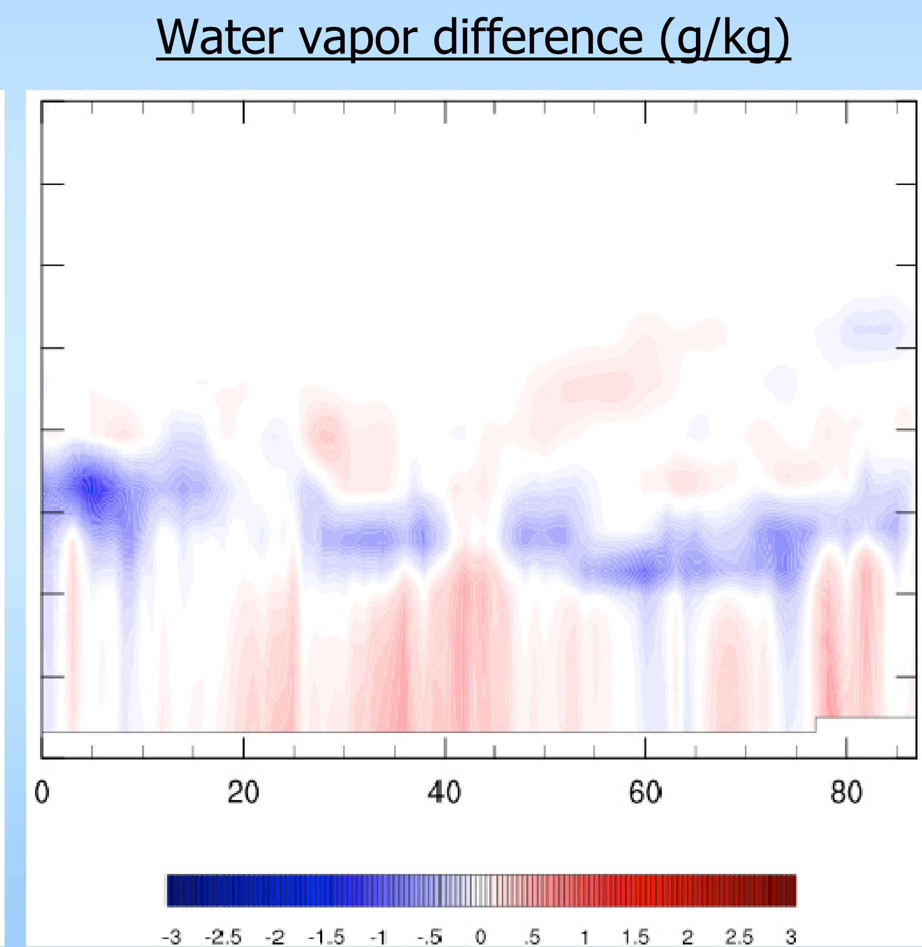
Domain setup for WRF-Chem



- Run coarser domain for 10 days with and without fires
- High resolution simulation starting on July 3, 2004 for 2 days, with and without fires. Initial and boundary conditions from (1)
- Fires initialized using WF-ABBA, MODIS, as well as aerial and ground observations
- No convective parameterization for D2
- Both domains have full physics and chemistry, including aqueous phase

Cross section: 0000UTC, July 4, 2004
Before clouds and precipitation: average over 5 grid points into and out of the cross section

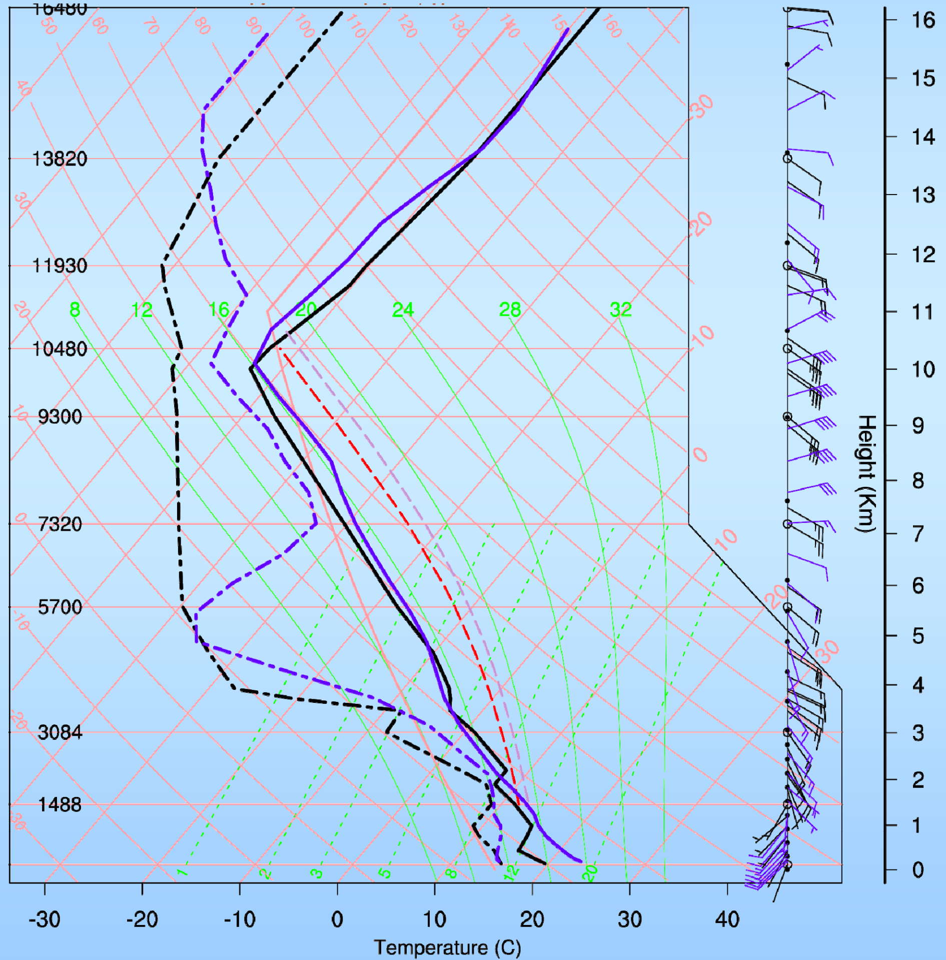




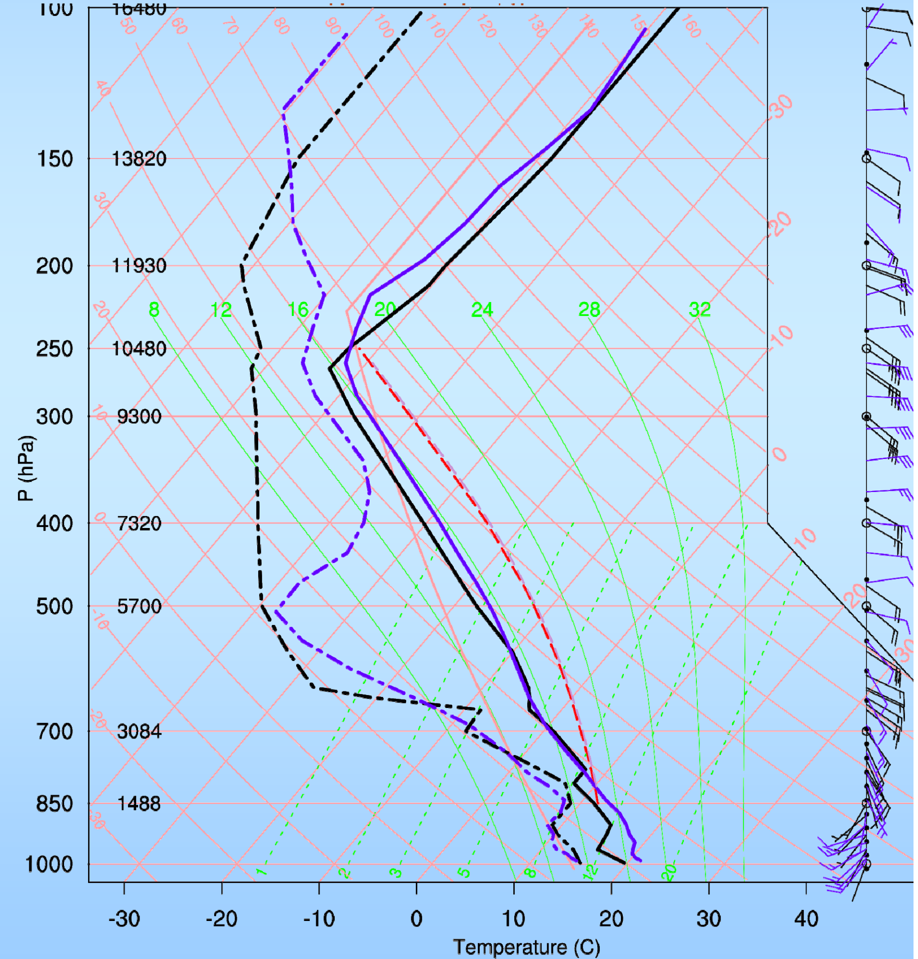
Direct and Semi-direct effect using WRF-Chem

24 hr forecast (blue) and observed (black) sounding for Fairbanks, Alaska, 4 July 2004 00UTC

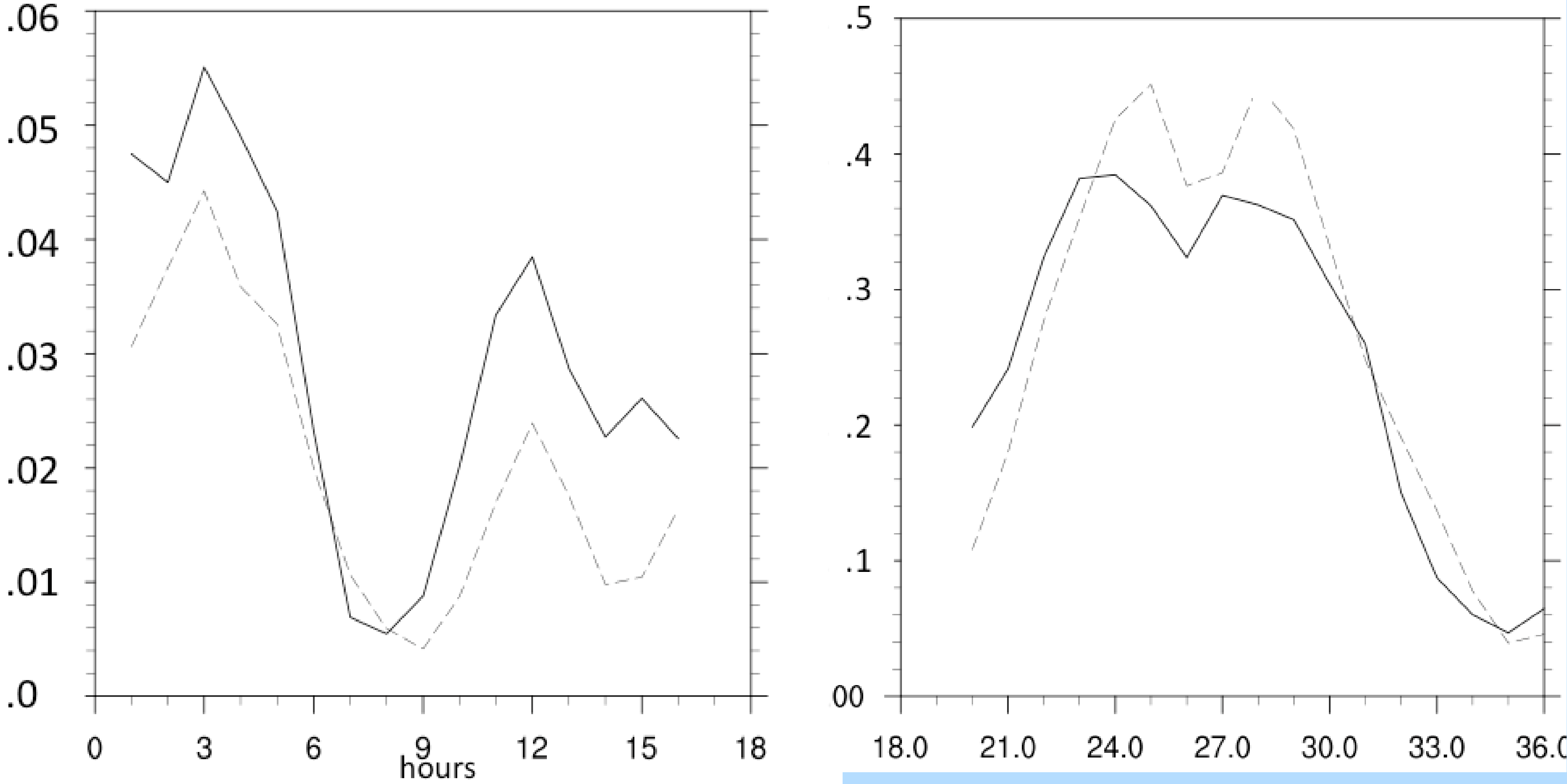
Without Fires



With Fires



Direct and indirect effect with WRF-Chem

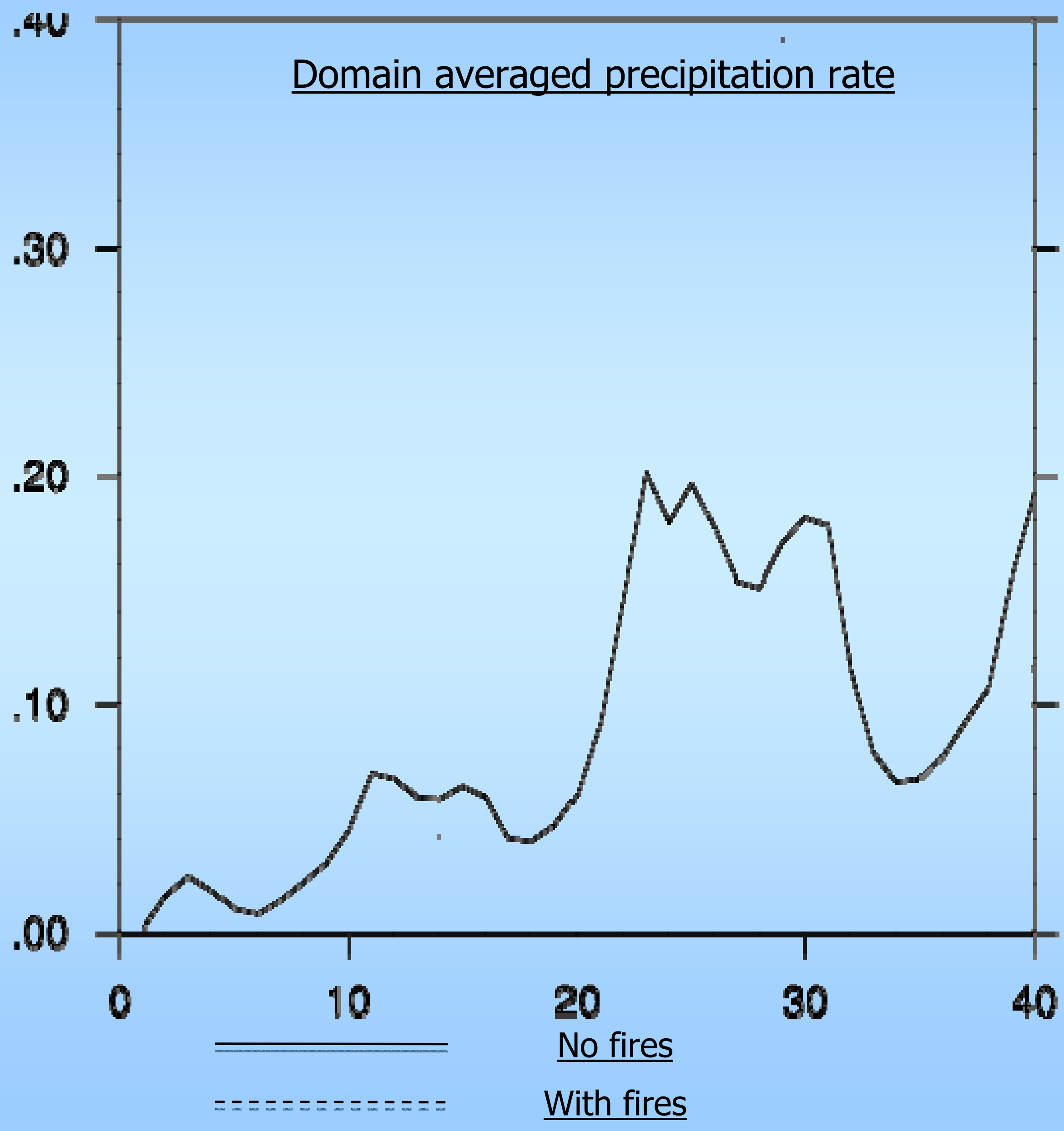


Domain averaged precipitation (mm/hr)

No fires

With fires

D01 (dx=10km) averaged over D02



Differences can be identified!

Direct and semi-direct effect maybe significant for weather forecasting even on a timescale of a few days

***Problem:** It is currently still very difficult to predict aerosol concentrations with better accuracy than climatology or persistence!!!*

***However:** It should be easy to beat persistence when strong signals exist (fires, dust, heavy pollution)*

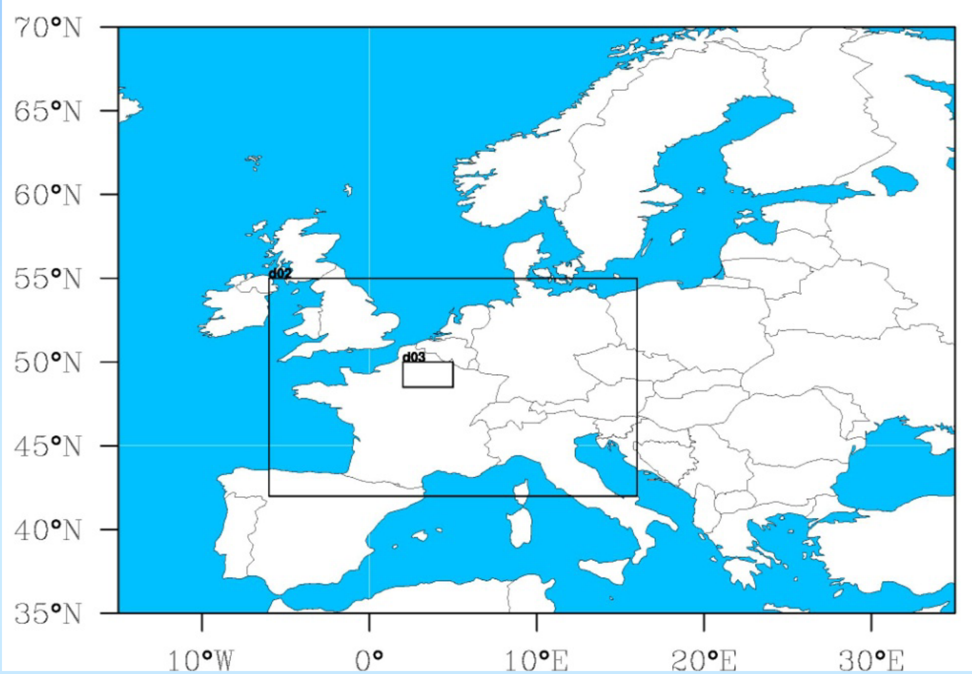
WRF/Chem-MADRID Study for Europe

By Yang Zhang (NCSU)

WRF/Chem-MADRID Study for Europe *(Y. Zang et al, 2011)*

Simulation Domain and Model Setup

- **Period:** 1-31 Jan./Jul. 2001
- **Domain:** 100×70(D01), 177×105(D02), 111×56(D03)
- **Horizontal resolution:** 0.5°/0.125 °/0.025°
- **Vertical resolution:** 23 layers (up to 100 mb)
- **Emissions:**
  - Anthropogenic gases/PM: EMEP 2001
  - BVOCs/sea-salt/dust: online
- **Meteorology IC and BC:**
  - NCEP/FNL reanalysis
- **Chemical IC and BC:**
  - Global-through-Urban WRF/Chem
- **Gas-phase chemistry:**
  - CB05
- **Aerosol module:**
  - MADRID
- **Cloud chemistry module:**
  - CMU mechanism
- **Aerosol-cloud interaction:**
  - Abdul-Razzak and Ghan (A-R&G)
- **Scenarios:**
  - Baseline emissions
  - No PM emissions, no secondary PM



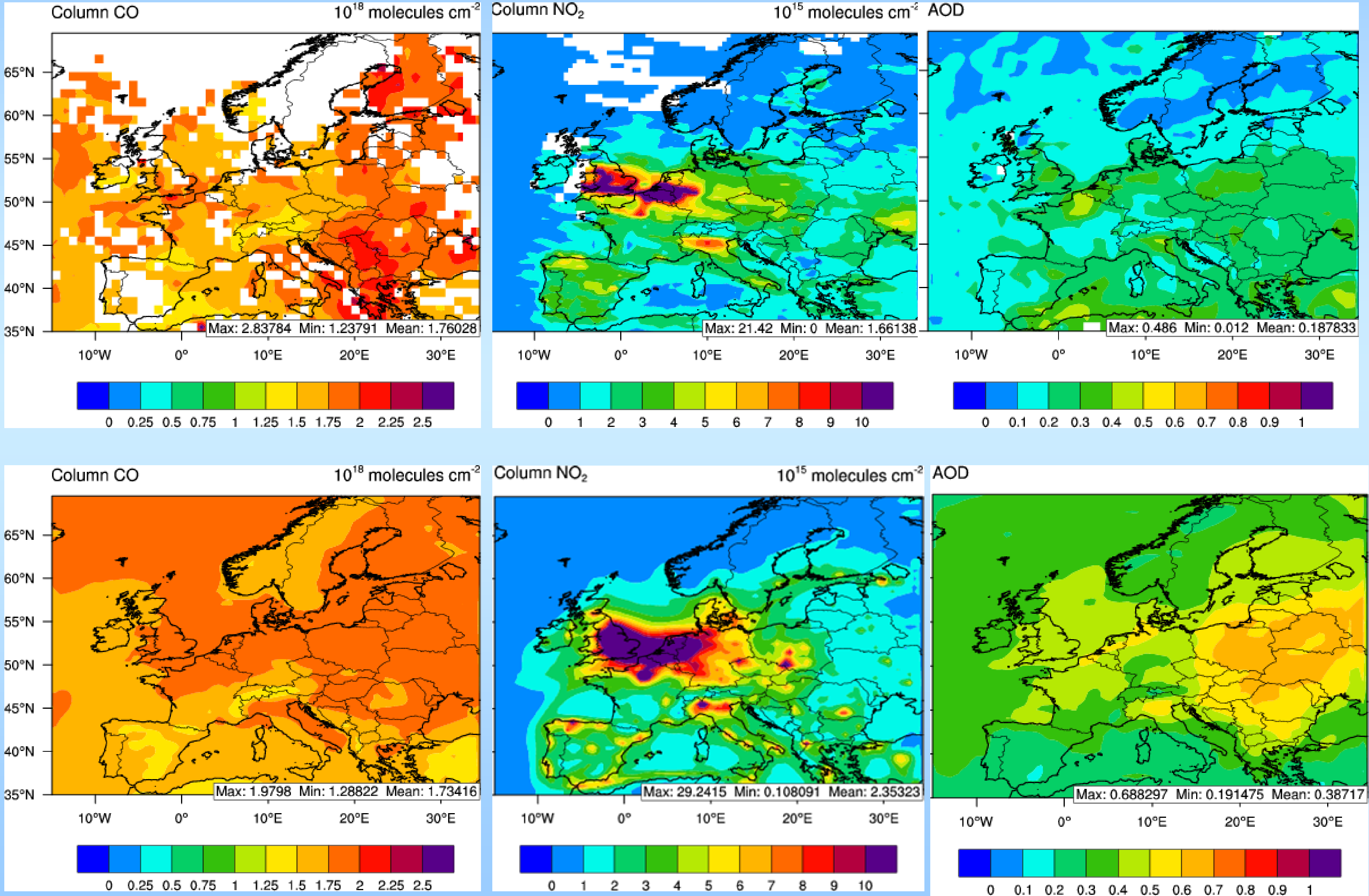
- **Data for model evaluation:**
  - NCEP : T, P, QV, RH, WSP, WDR (surface and aloft)
  - NCDC: T, RH, WSP, Precip
  - ECA&D: Precip
  - AirBase: SO_2, NO_2, CO, NH_3, O_3, $PM_{2.5}$, PM_{10} & PM_{10} species
  - EMEP: SO_2,NO_2, HNO_3,NH_3, O_3, $PM_{2.5}$, PM_{10}, & PM_{10} species
  - BDQA: SO_2,NO_2, O_3, CO, PM_{10}
  - MOPITT: CO
  - GOME: NO_2
  - TOMS/SBUV: Tropospheric Ozone Residual (TOR)
  - MODIS: AOD, CF, COT, PWV, CWP, CCN

Obs vs. Sim Spatial Distribution of Column CO, NO_2 & AOD in Jul

CO, NMB = -1.8% NO_2, NMB = 46.1% AOD, NMB = 106.3%

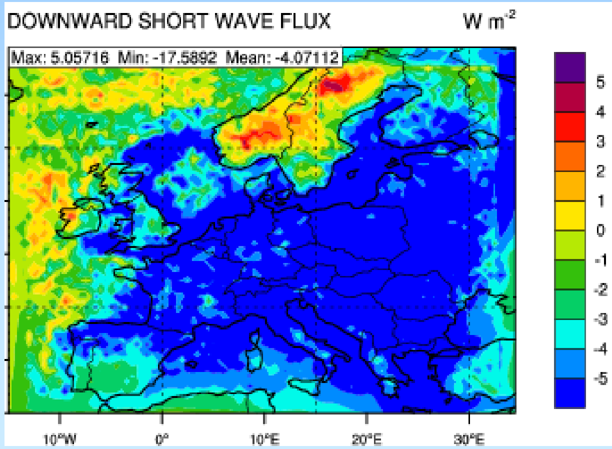
Obs

Sim



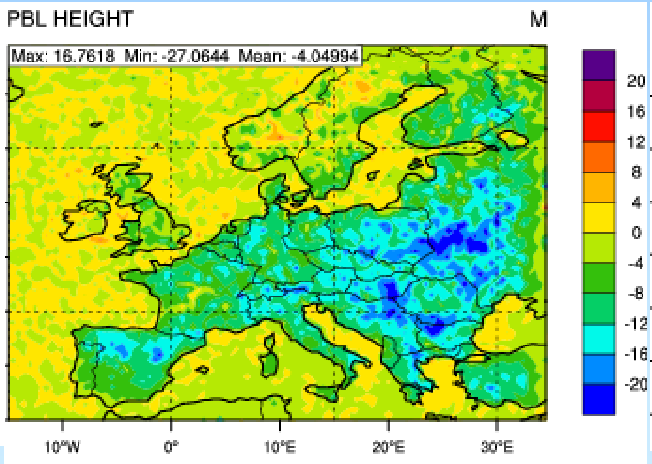
Direct, Semi-Direct, and Indirect Effect of PM in Jul

Downward Shortwave Flux



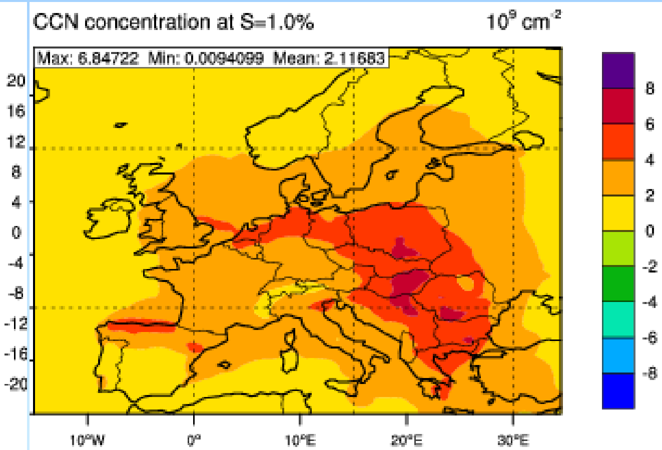
Max: -17.6 W m^{-2} or -6.7%

PBL Height



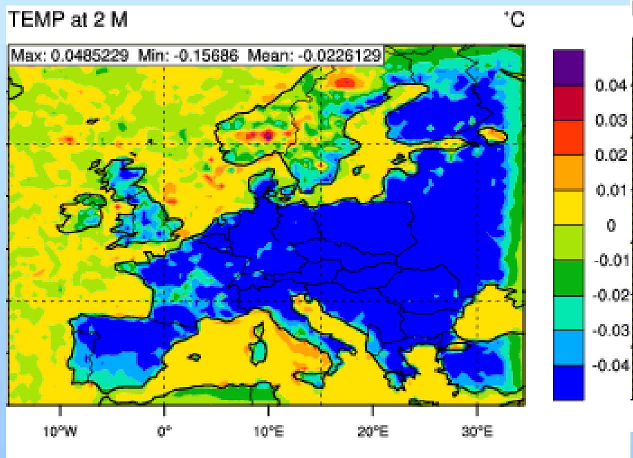
-27.1 m or -5.6%

Cloud Condensation Nuclei



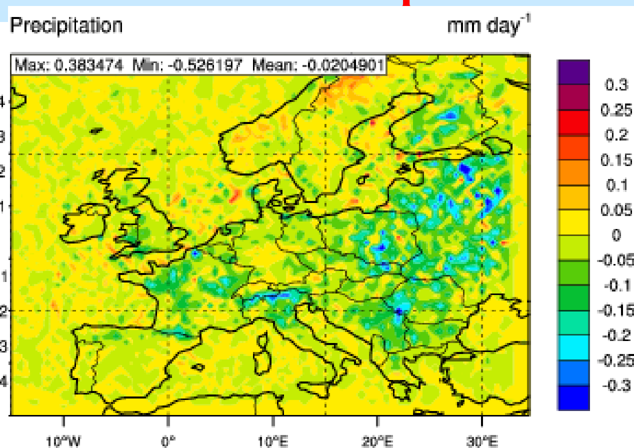
6.4 × 10^{9} cm^{-2} or 756.4%

Temp at 2-m



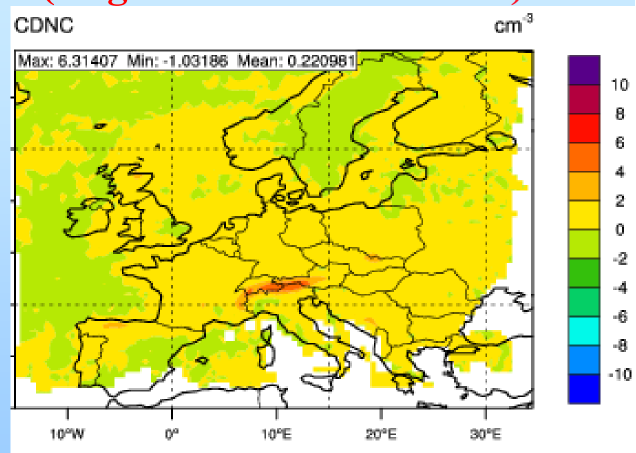
Max: -0.2 °C or -1.1%

Total Precip



-0.5 mmday^{-1} or -100%

Cloud Droplet Num. Conc. (Avg between 933-868 mb)



6.3 cm^{-3} or 800.5%

Aerosol Direct and Semi-Direct Effects in July: China, U.S., and Europe

$PM_{2.5}$ Mass

Direct Effects on Shortwave Radiation

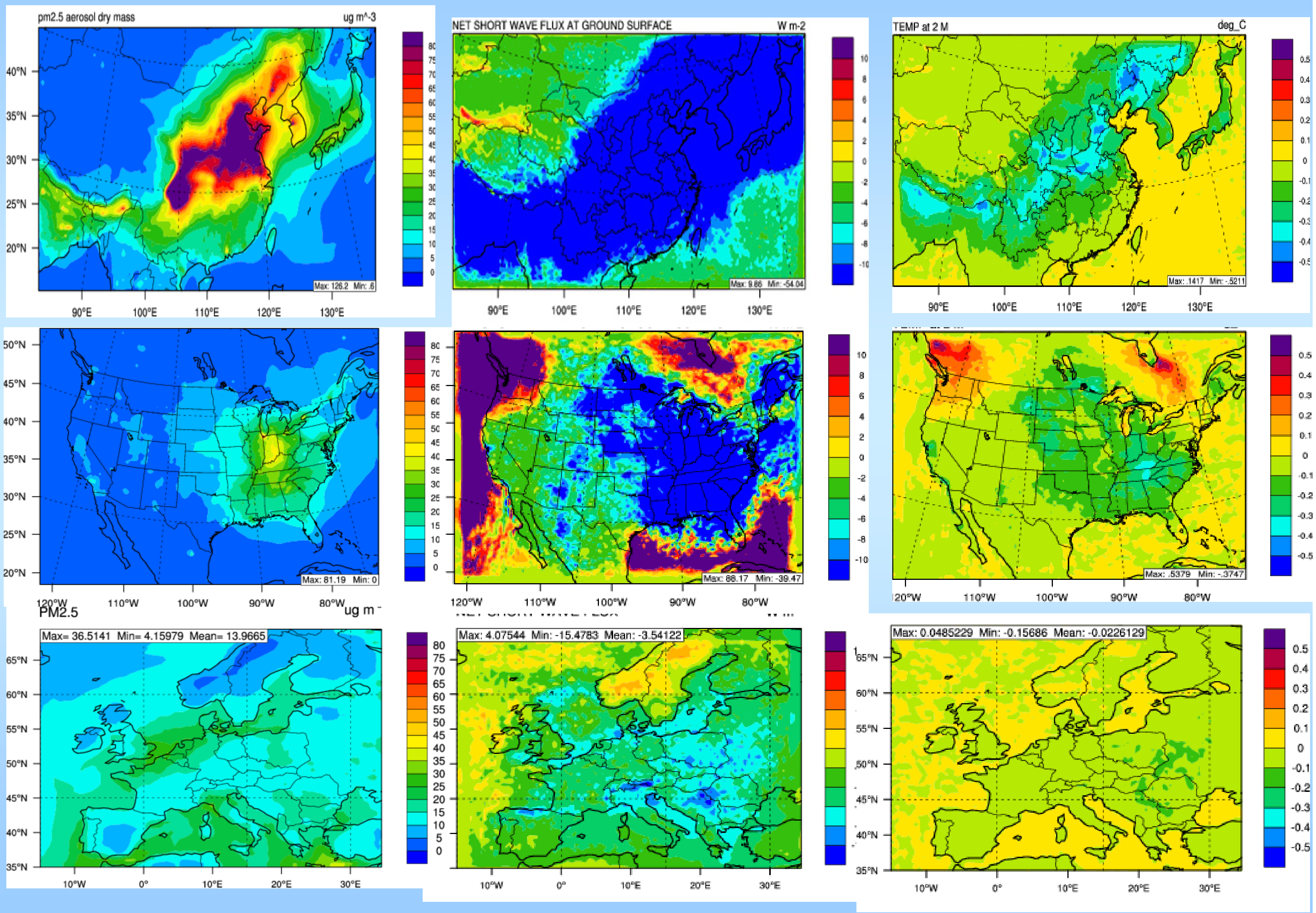
Semi-direct Effects on T2

Absolute Difference

China

U.S.

Europe



Aerosol Semi-Direct and Indirect Effects in July: China, U.S., Europe

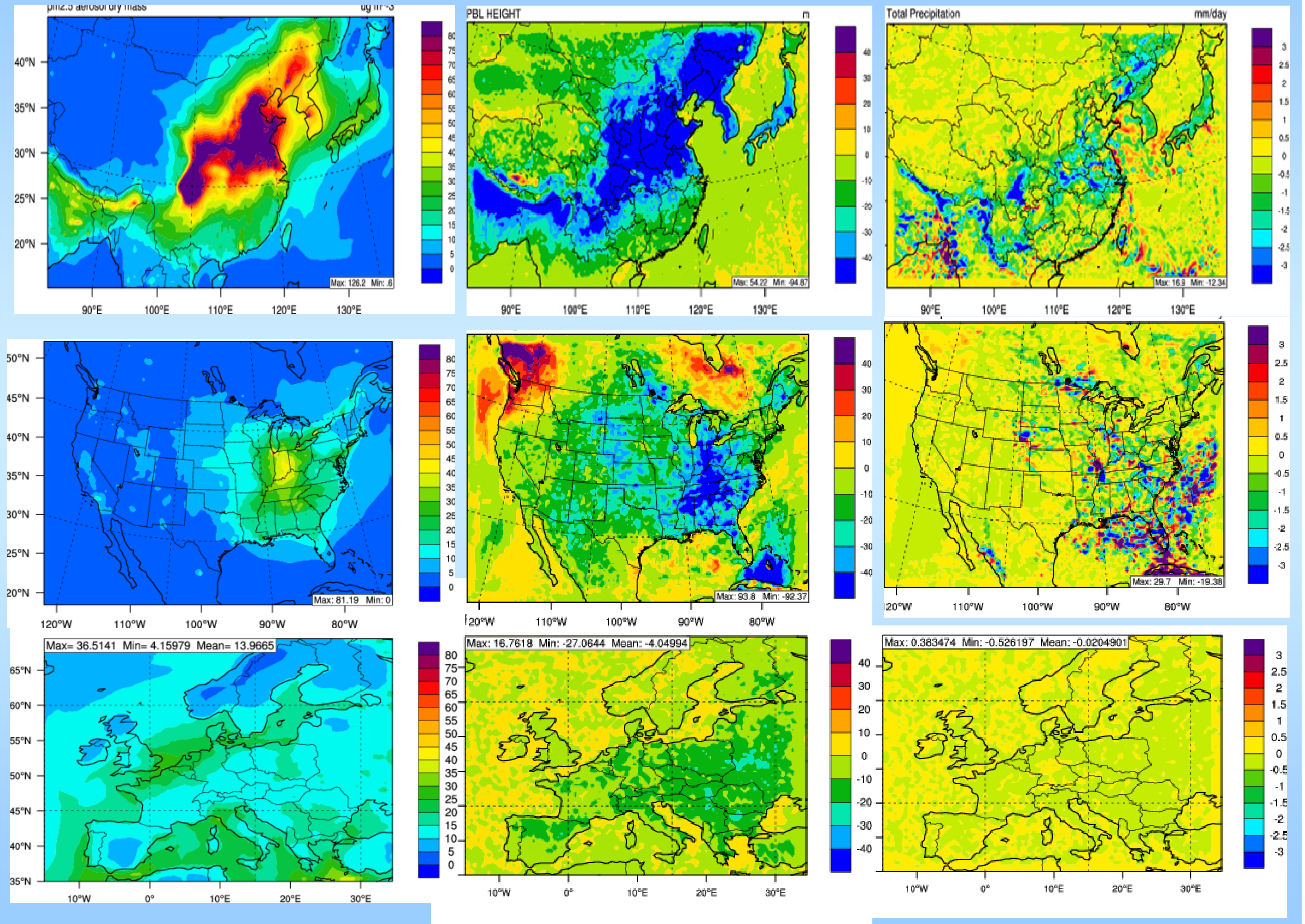
$PM_{2.5}$ Mass | Semi-Direct Effects on PBL Height | Indirect on Precipitation

Absolute Difference

China

U.S.

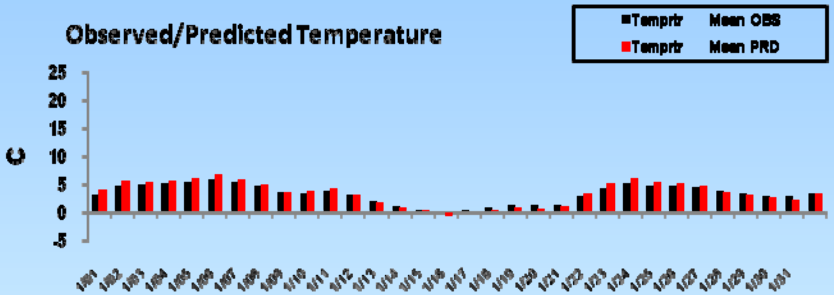
Europe

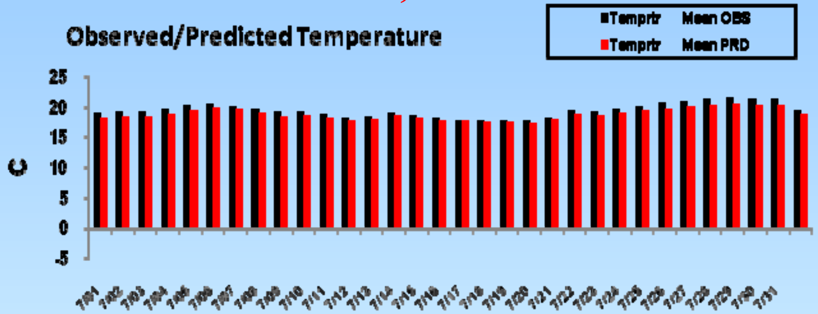


Obs vs. Sim Temporal Variation of Meteorology

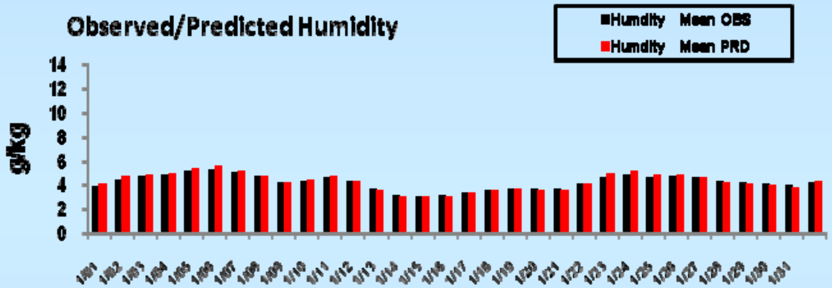
Jan, 2001 | **Jul, 2001**

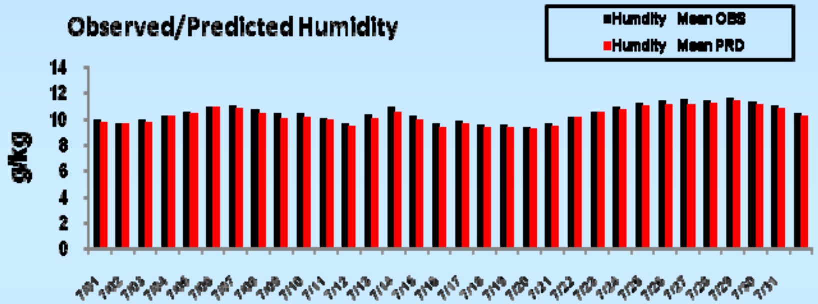
T2



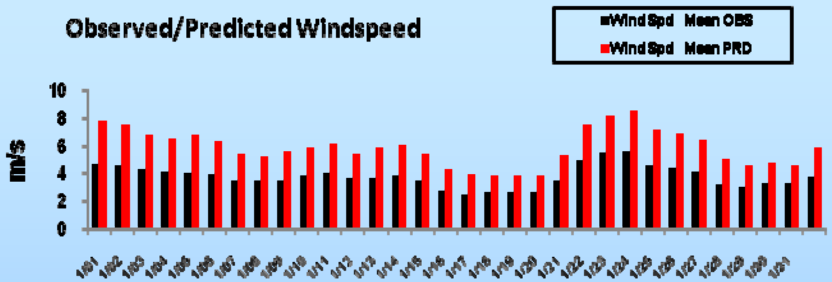


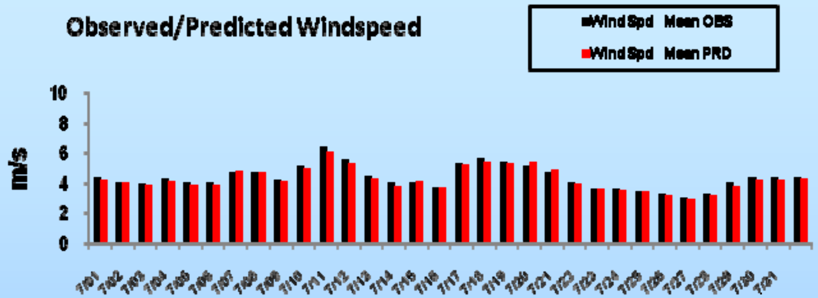
QV2



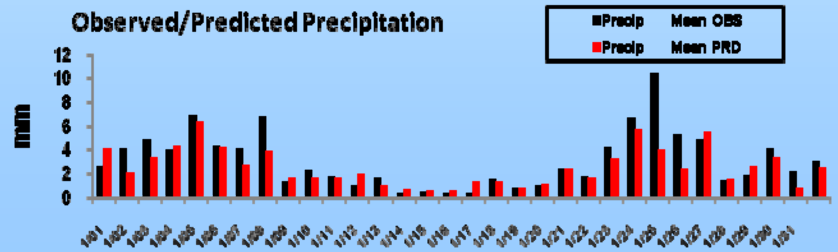


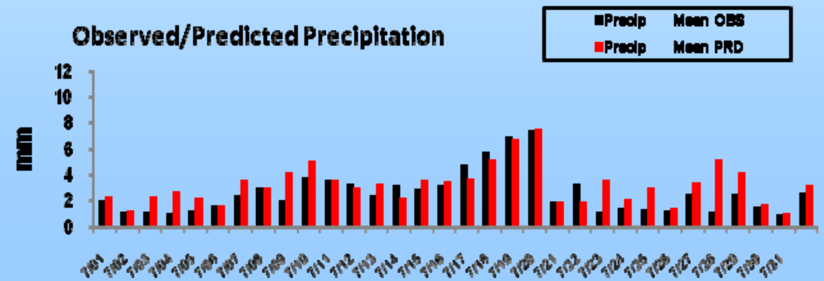
WSP10





Precip





Major Findings and Future Work

- **WRF/Chem-MADRID demonstrates overall good skills to reproduce observations**
- **Aerosol feedbacks to radiation, meteorology, and cloud microphysics over Europe**
  - **Aerosols decrease shortwave radiation by as much as -6.7% (domainwide mean: -1.3%)**
  - **Aerosols decrease T2 by as much as -0.2 °C (domainwide mean: -0.02°C)**
  - **Aerosols decrease wind speed by as much as -1.9% (domainwide mean: -0.1%)**
  - **Aerosols decrease PBL height by as much as -5.6% (domainwide mean: -1.0%)**
  - **Aerosols increase to CCN by up to a factor of 11 (domainwide mean: a factor of 31)**
  - **Aerosols increase to CDNC by up to a factor of 9 (domainwide mean: 11.7%)**
  - **Aerosols decrease precipitation by as much as -100% (up to -8% over most areas)**
- **With current model treatments, the magnitude of aerosol effects over Europe is small as compared with that over North America and Asia for this episode, but non-negligible.**
- **Examine sensitivity of simulated aerosol effects to horizontal grid resolution**
- **Improve aerosol-cloud-precipitation representations (e.g., new parameterizations for new particle formation and early growth and coarse PM; effects of aerosol on convective clouds and precipitation, and high level clouds such as anvils and cirrus; effect of aerosols such as dust to ice crystal formation, and aerosol indirect effects through ice nucleation)**

WRF-Chem / WRFPLUS for China

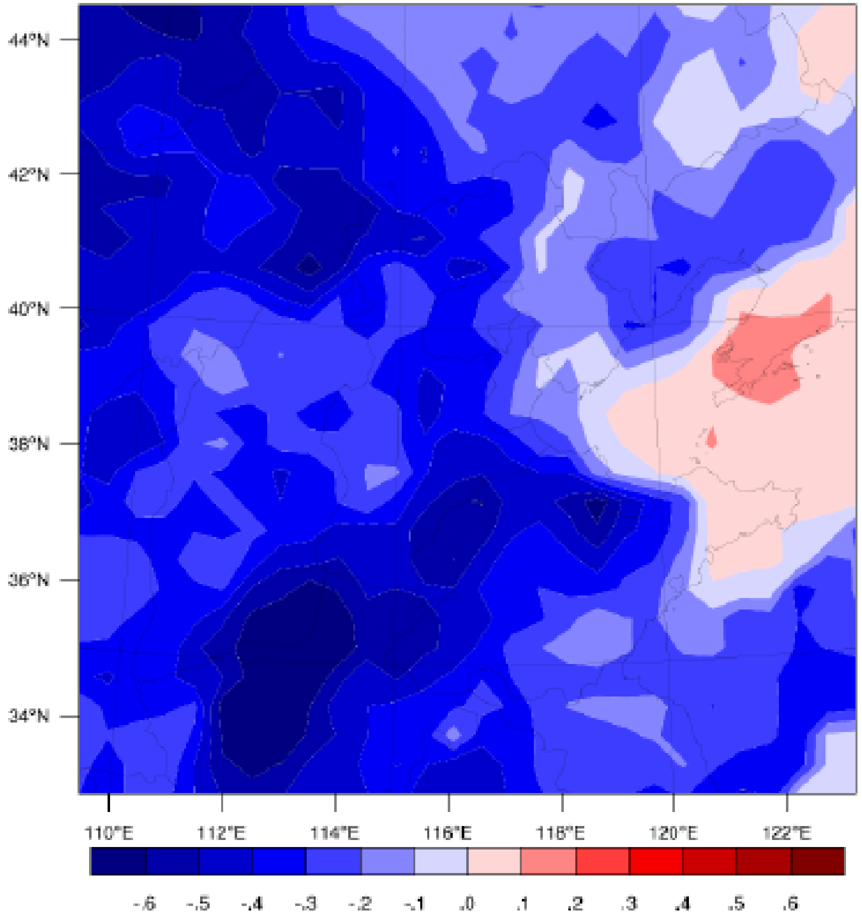
Greg Carmichael et al. (University of Iowa)

Aerosol Net Effects

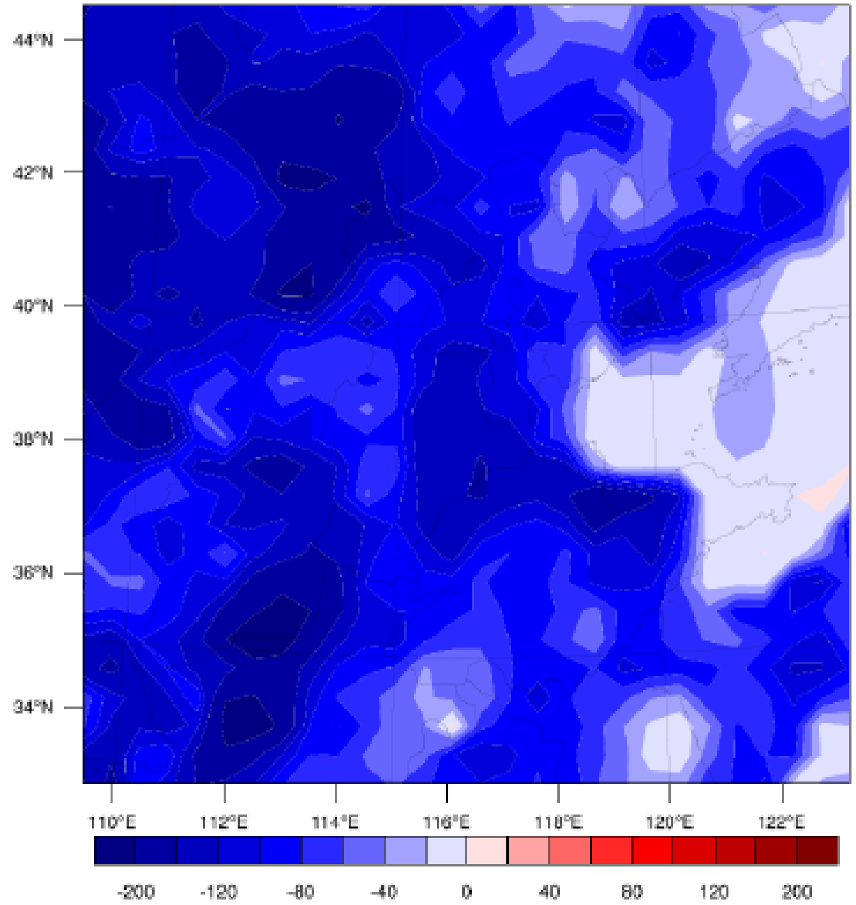
Daytime means (Feedbacks – pure WRF)

Net cooling Up to – 0.8 °C

Up to – 100 to -150 m

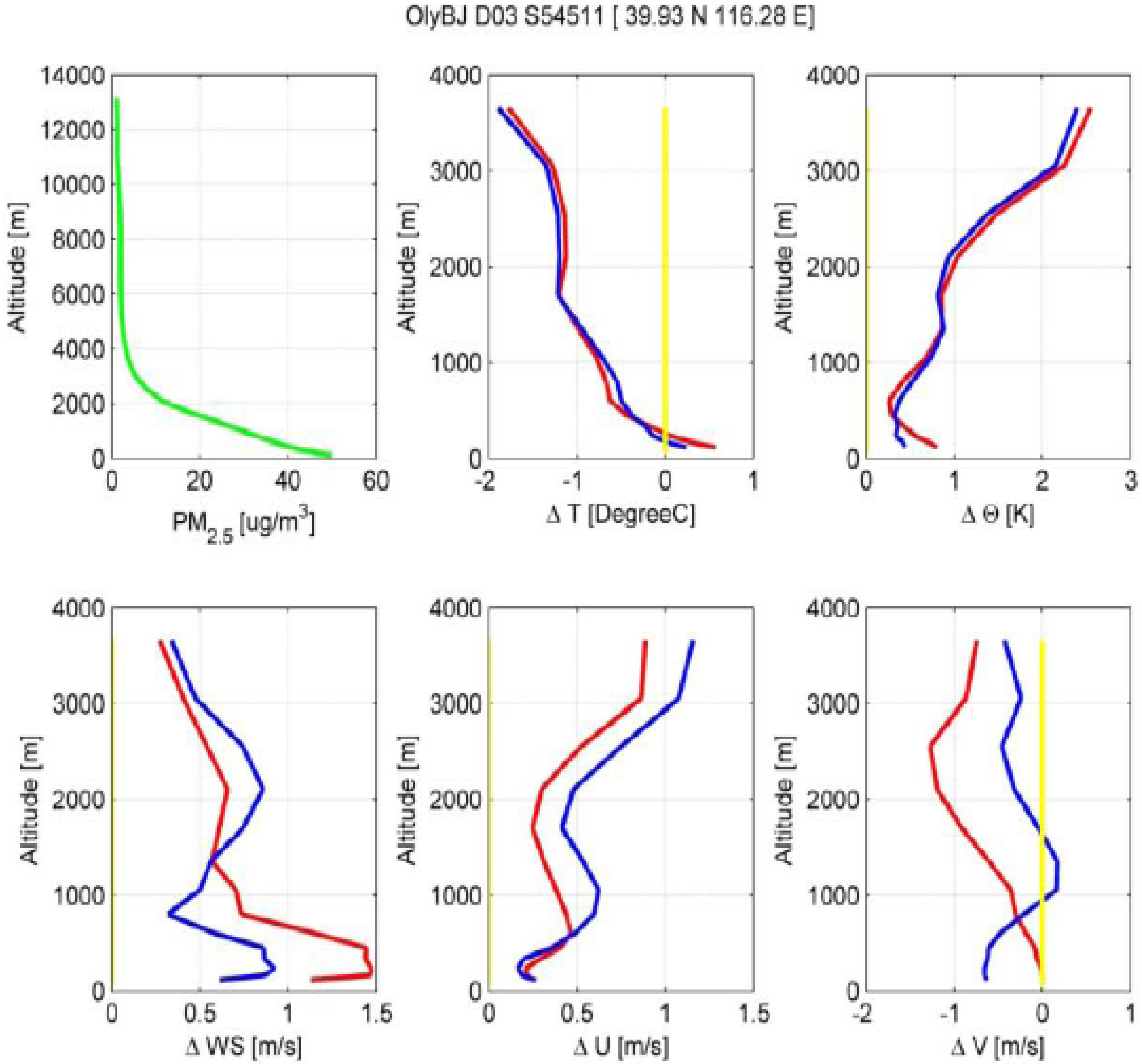


T2



PBLH

Feedbacks push the modeled meteorology towards the observation, especially near the ground surface



Green: PM2.5 vertical profile

Yellow: ideal case (0)

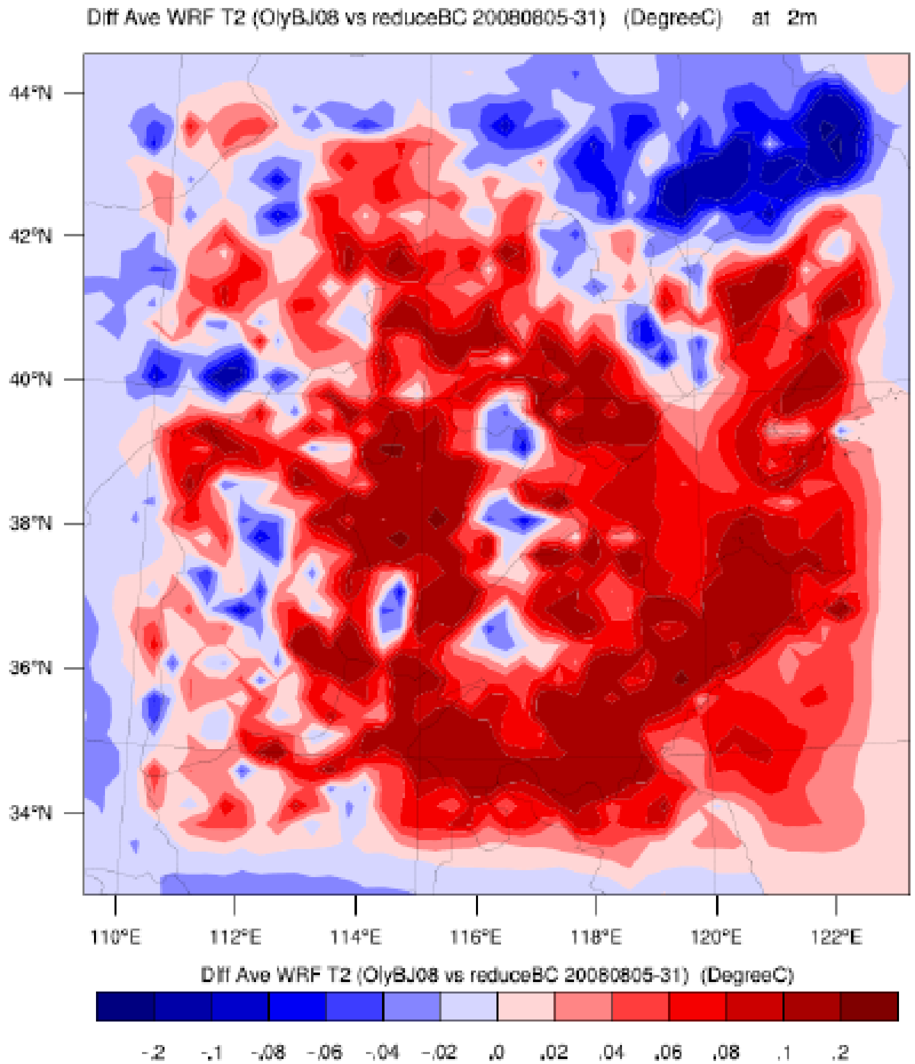
Red: [WRF pure meteo] – OBS

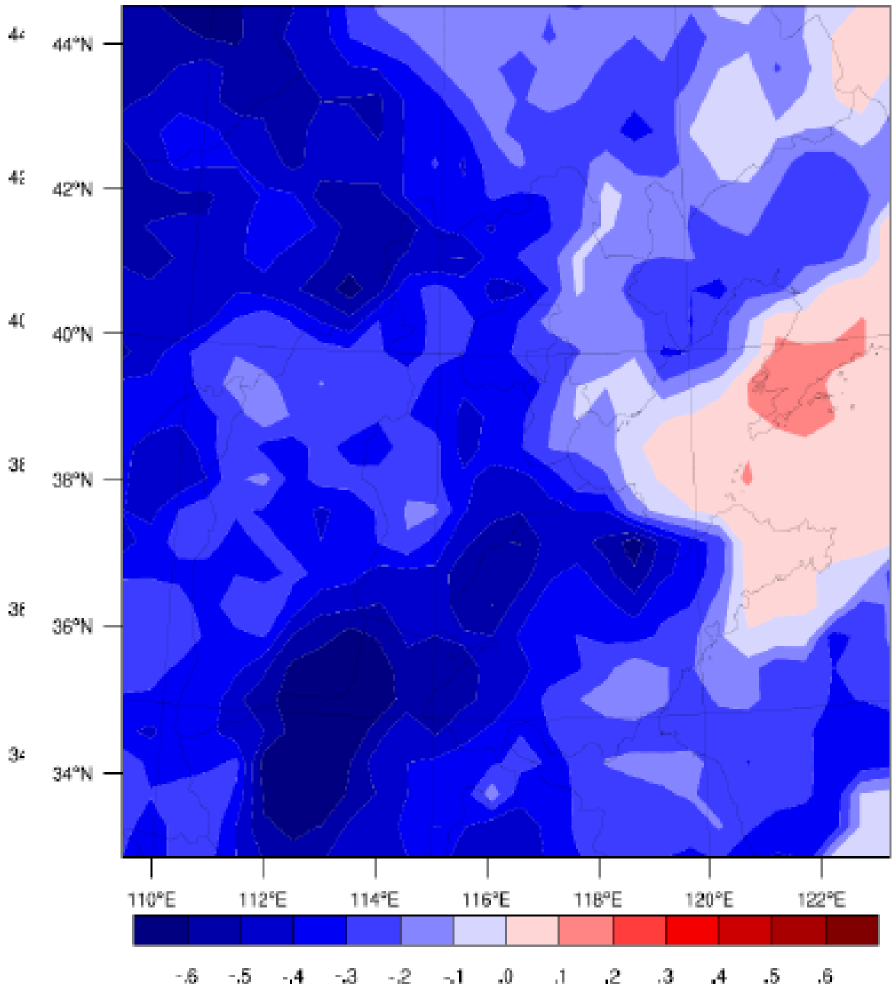
Blue: [WRF-Chem meteo] – OBS

Sensitivities to BC Aerosol

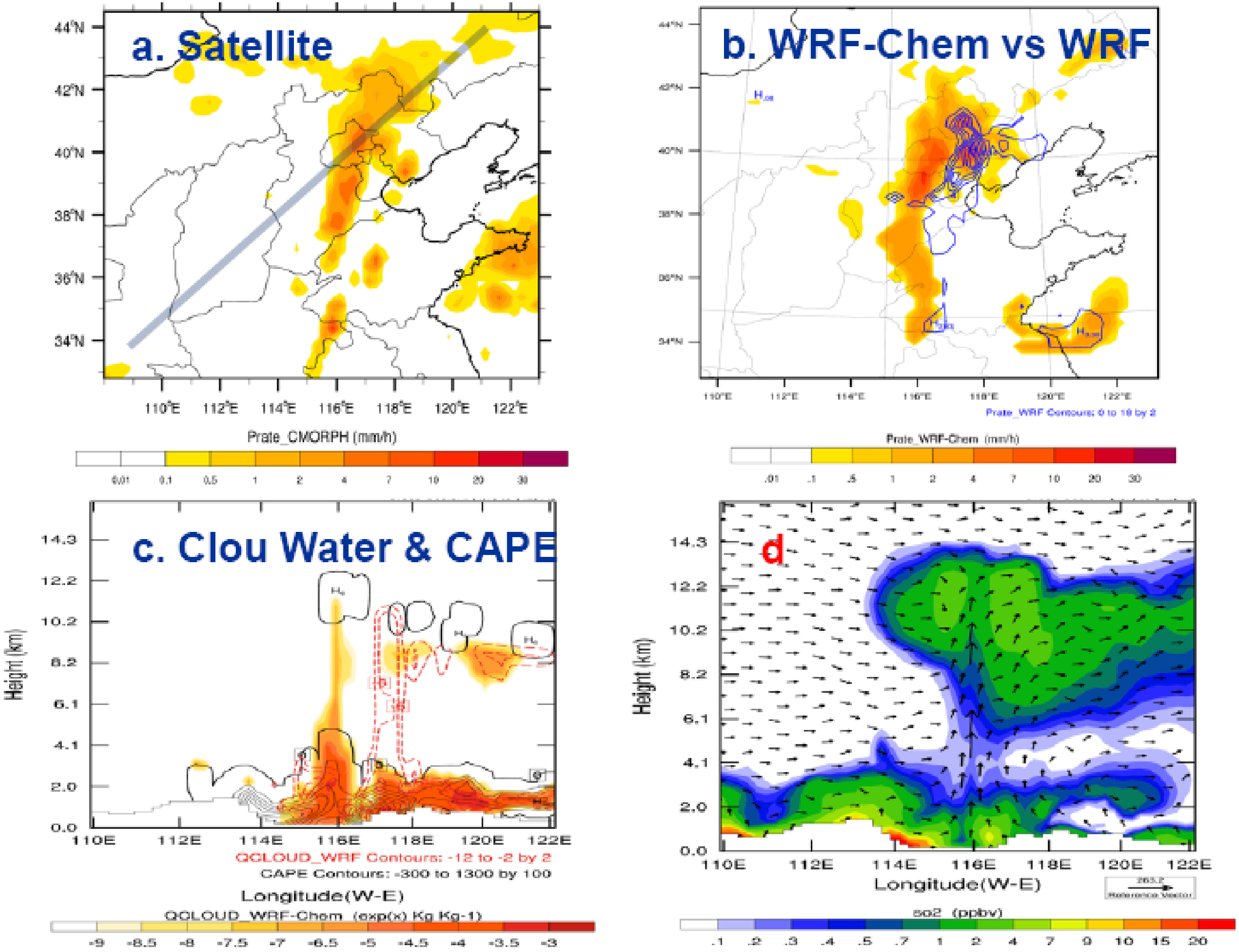
$\Delta T(2m)$

BC only | **All aerosol effect**



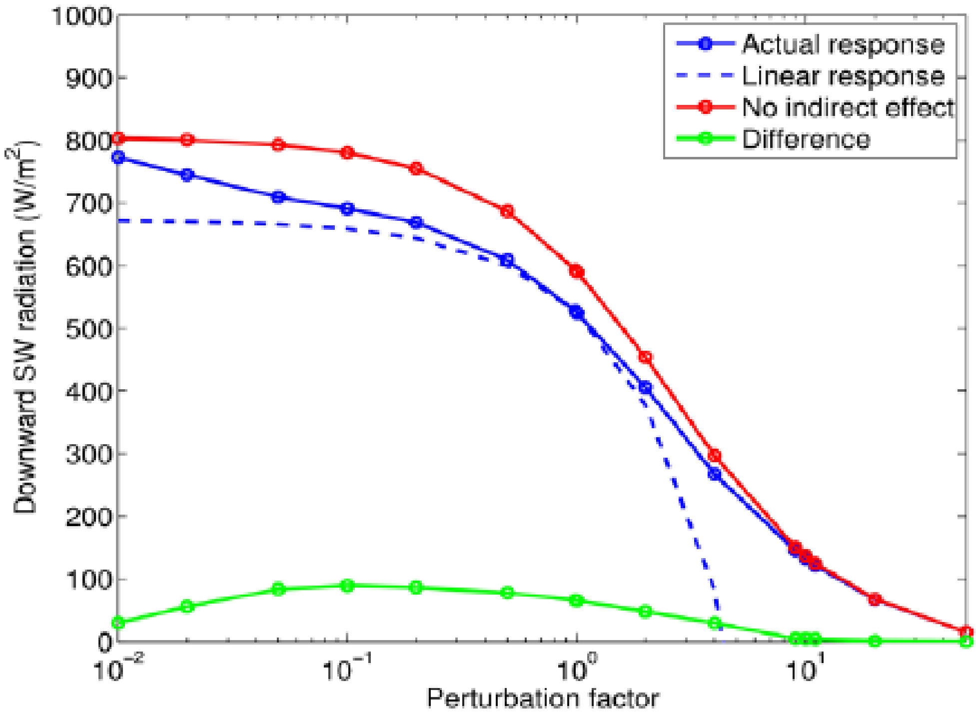


Feedbacks Lead To Better Precip Predictions



Aerosol climate interactions sensitivities

- Develop stand alone version of WRF modules (Short wave radiation, Optical properties, Aerosol activation) and test in a column over megacities (e.g. Beijing) and clean conditions (e.g. VOCALS experiment).
- Building of adjoints of direct and indirect effects in WRF-Chem:
  - To analyze backwards sensitivities from radiation and cloud properties to aerosols (distribution, loading, composition, altitude).
  - Updated WRFPLUS development



SW radiation response to different aerosol loadings with and without indirect effects (clouds over Beijing case)

C-IFS for global scale

By ECMWF: Flemming et al. 2011

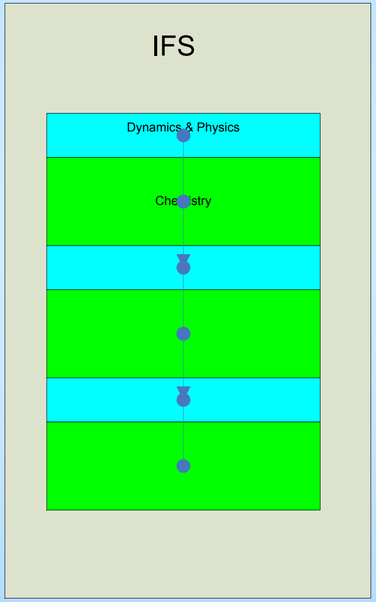
Integration of chemistry & aerosol modules in ECMWF's integrated forecast system (IFS)

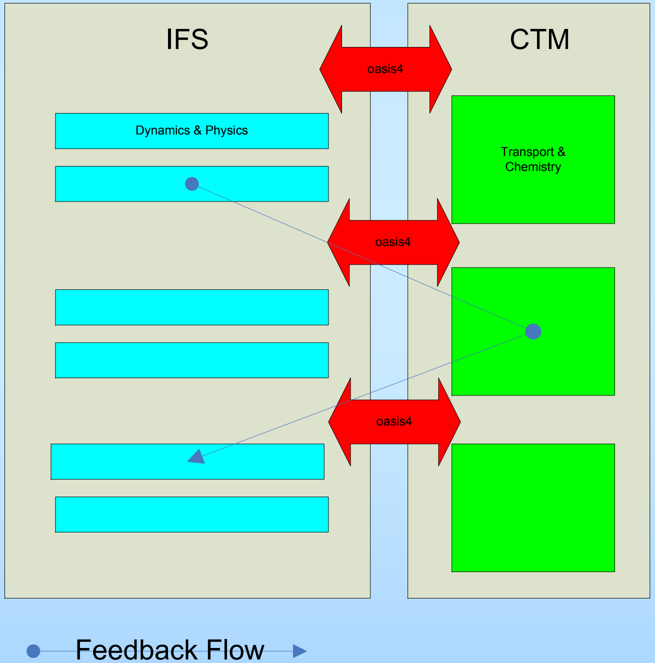
C-IFS
On-line Integration of Chemistry in IFS

Coupled System
IFS- MOZART3 / TM5

Developed in MACC

10 x more efficient than Coupled System





Developed in GEMS
Used in MACC

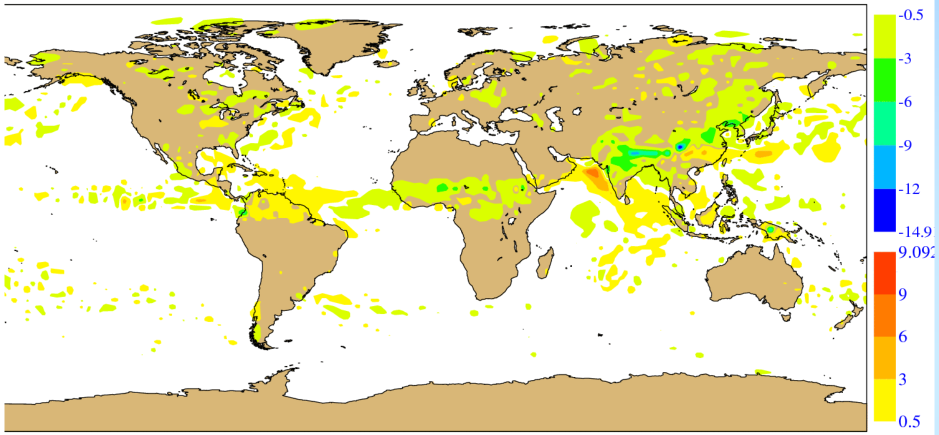
Integrated System
Feedback: fast
Flexibility: low

Coupled System
Feedback: slow
Flexibility: high

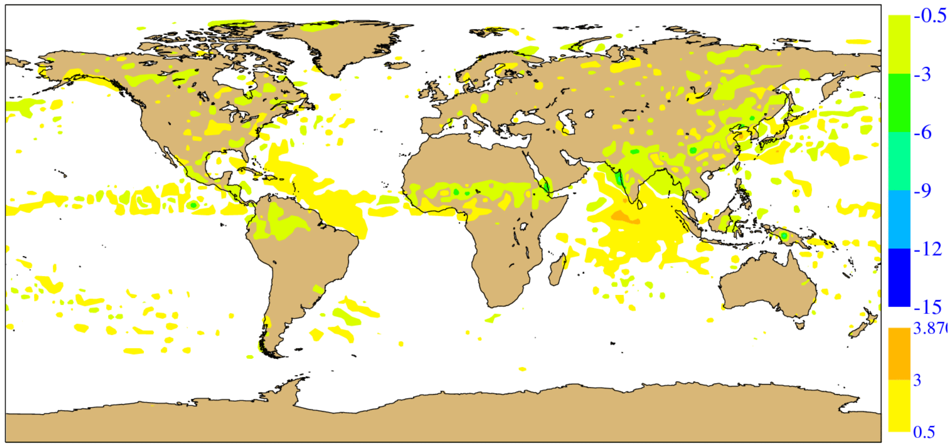
Flemming et al. 2009

Monthly Mean Total precipitation difference (mm/day) July

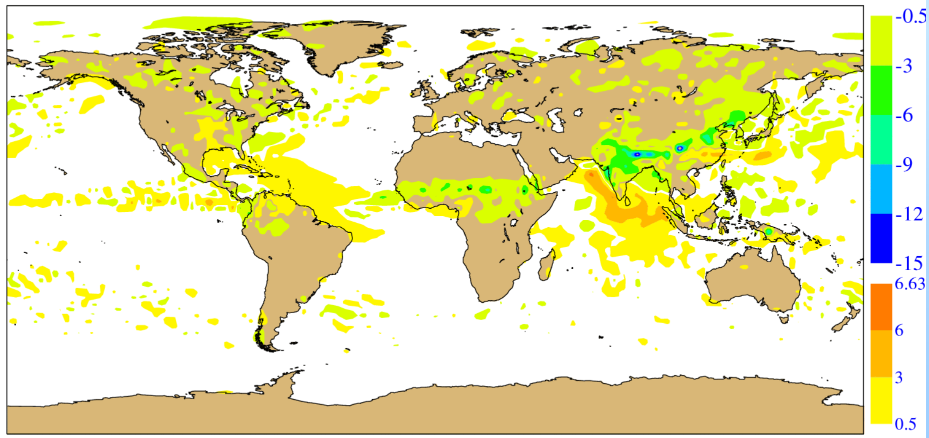
Direct - Base



inDirect - Base



Direct & inDirect - Base



J-J Morcrette

Conclusions *(Grell and Baklanov, 2011)*

- Although we may continue to develop and run modeling systems of Earth system components separately, a scientific perspective would argue for an eventual migration to integrated modeling systems that allow two-way interaction of physical and chemical components of chemical weather forecasting systems.
- While this may be the obvious approach for air quality forecasting, more research and discussion may be needed for NWP.
- AQ and NWP communities should work more closely together.
- National weather centers are advised to include chemistry/aerosol interactions into NWP systems extending their forecasts to the chemical weather as well.
- Centers that are responsible for AQ forecasting should seriously consider online modeling as a necessary part of their suite of forecasts. Additional advantages will arise from cross evaluations for both disciplines. Chemical species will allow identification of short comings in currently used forecast models as well as lead to better use of meteorological data assimilation.
- Other outcomes from such collaboration and the online coupling may include benefits for:

(i) meteorological weather forecasting (e.g., in urban areas, severe weather events, fog, and visibility, UV-radiation and solar energy, etc.),

(ii) chemical weather/air quality and bio-meteorology forecasting,

(iii) seasonal and decadal air quality/climate prediction,

(iv) global and regional projections of the climate/Earth system.

Recommended literature and Sources:

- http://www.eumetchem.info - *COST7 ES1004 web-site with EGU-COST presentations*
- http://meetingorganizer.copernicus.org/EGU2011/session/7498 - EGU-2011 section
- Grell, G. and A. Baklanov, 2011: Coupled Modeling for Forecasting Weather and Air Quality. Atmospheric Environment, doi:10.1016/j.atmosenv.2011.01.017.
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- Baklanov A., Mahura A. (Eds.): Interactions between Air Quality and Meteorology, Deliverable D4.3, MEGAPOLI Scientific Report 10-10, MEGAPOLI-13-REP-2010-03, 2010, 48p, ISBN: 978-87-993898-3-4.
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