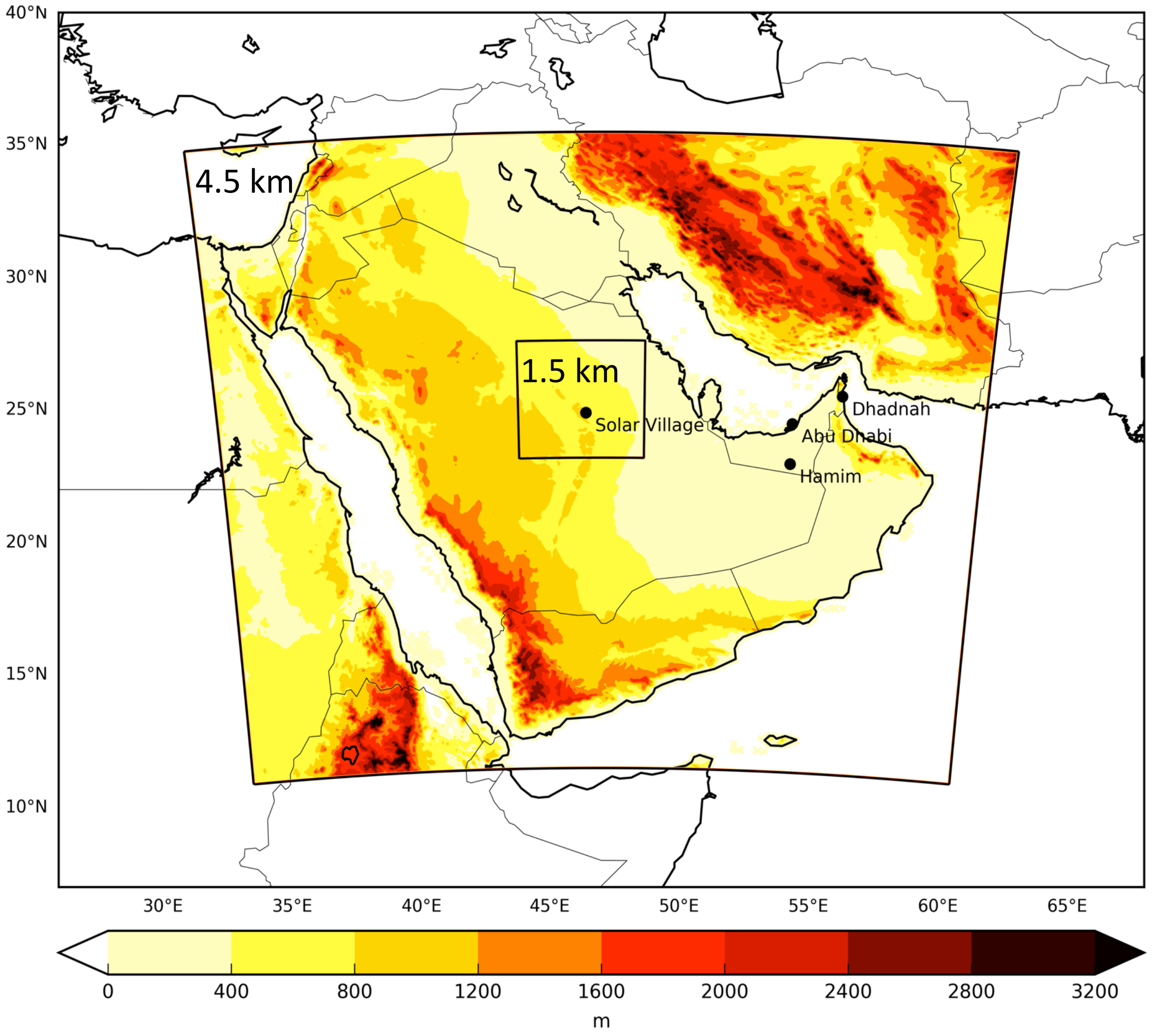
Evaluation of cloud-resolving modeling of haboobs using in-situ and remotely sensed observations

Anatolii Anisimov (1), Duncan Axisa (2), Suleiman Mostamandi (1), Paul A. Kucera (2), Georgiy Stenchikov (1)

(1) King Abdullah University of Science and Technology (KAUST), Physical Sciences and Engineering Division, Thuwal, Makkah, Saudi Arabia
(2) National Center for Atmospheric Research (NCAR), Boulder, CO, USA



Motivation

- Evaluate the **WRF-Chemistry** performance to simulate the mesoscale dust storms in the Arabian Peninsula. **Arabian Peninsula is one of the major dust generation regions that at present is severely under-sampled** (only single dust observational campaign in 2008)!
- Estimate the generation and physical properties of dust uplifted by gust front outflows in desert environment.
- Assess the mineral dust size distribution in **WRF-Chem** configured with **MOSAIC** aerosol scheme.

Aircraft measurements

- The key element of the study is the unique dataset of aircraft measurements performed during the "Kingdom of Saudi Arabia Assessment of Rainfall Augmentation". Features the measurements of aerosol size distribution within the haboob "dust cloud".

Model

- **Cloud-resolving WRF-Chemistry – 2 nested domains (4.5 + 1.5 km)**
- ECMWF 25 km operational analysis BC
- **MOSAIC** 8 bin aerosol scheme w. aerosol water stage and aqueous chemistry

Model setup & data

WRF-Chemistry setup

- 2 nested cloud-resolving domains (4.5 + 1.5 km) – convection parameterization has been turned off, 40 hybrid vertical layers
- **ECMWF 25 km operational analysis BCs**
- **Spectral nudging in both domains towards driving BC**
- **EDGAR-HTAP** anthropogenic emissions of gases and aerosols
- **CBMZ chemistry + MOSAIC aerosols (chem_opt=10):**

⇒ **MOSAIC 8-bin aerosol scheme**: 9 species: dust, BC, POM, sulfate, nitrate, chloride, ammonium, sodium, water (Zaveri et al., 2008)

⇒ **GOCART dust emission** + MODIS source function, **fixed size distribution** at emission is assumed (Kok et al., 2011)

⇒ **aerosol dry deposition in PBL** (Binkowski & Shankar, 1995)

⇒ **aerosol wet deposition** (in-cloud and below-cloud) (Easter et al., 2004 & Chapman et al., 2009) and **aerosol-cloud interactions (indirect effects)** (Gustafson et al., 2007 & Chapman et al., 2009), **coupled with Lin et al. microphysics**

⇒ **direct effects** (Zhao at al., 2013), **coupled with RRTMG radiation** in both SW and LW

⇒ sea salt emissions (Zhao et al., 2013)

⇒ aqueous chemistry (Fahey and Pandis, 2001)

Data

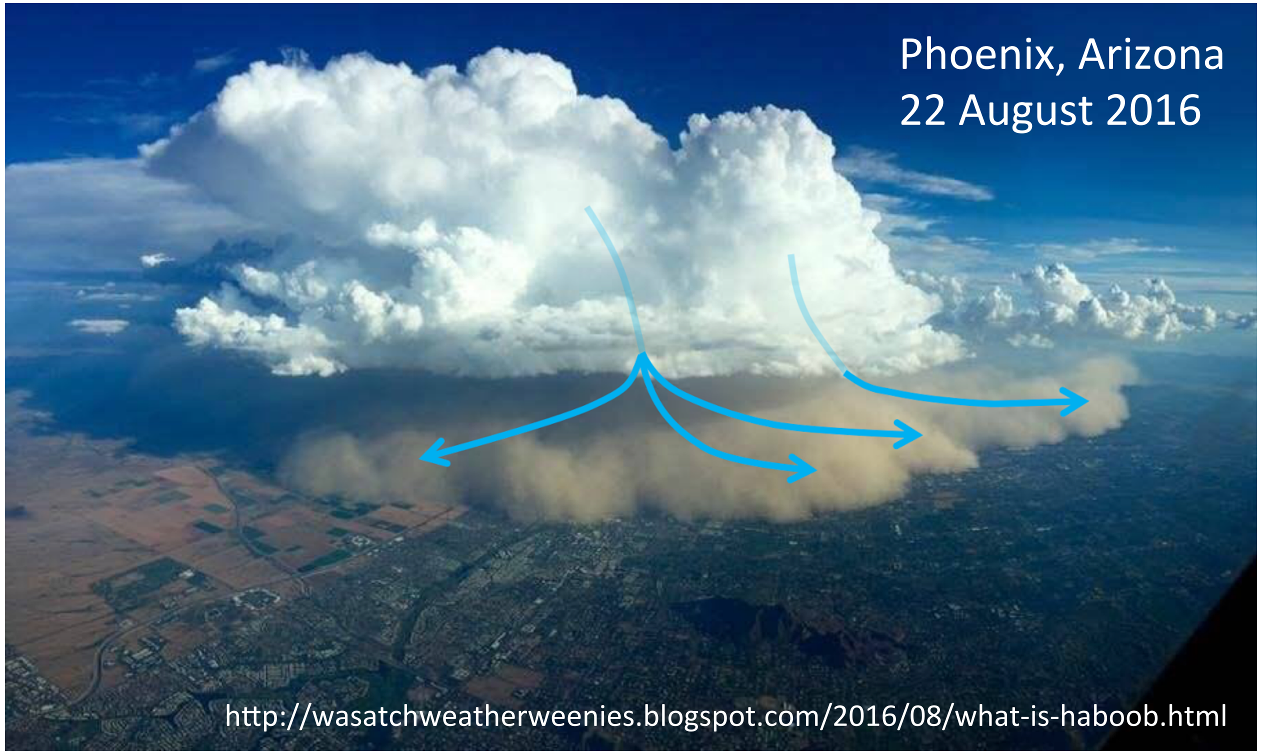
- NASA **MERRA-2** 50-km reanalysis (**assimilates AERONET & MODIS**)
- NASA **MODIS** Collection 6 combined Deep Blue/Dark target AOD
- **Meteosat SEVIRI** qualitative “**pink dust**” product (Lensky and Rosenfeld, 2008)
- **Meteosat SEVIRI AOD** product (Banks & Brindley, 2013)
- **AERONET** AOD & inversion products (column-integrated size distribution)
- **Aircraft aerosol number size distribution measurements (Posfai et al., 2013)**
- Meteorological radar measurements in Riyadh
- TRMM precipitation
- Weather station data for meteorological validation

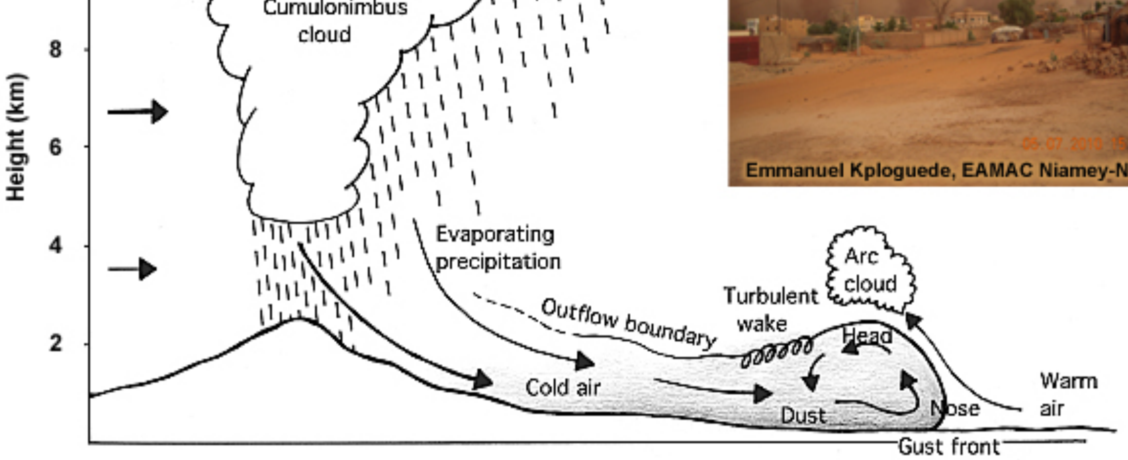
Outline

1. Introduction
    - Motivation & tools
    - Model setup & data
2. Brief theory. What is a haboob?
3. Synoptic situation during the observational campaign
4. Model evaluation
5. Aircraft measurements
    - Aircraft equipment
    - Observational cases
6. Model results
    - Convection & haboobs in the model and observations
    - Aerosol size distribution
7. Conclusions

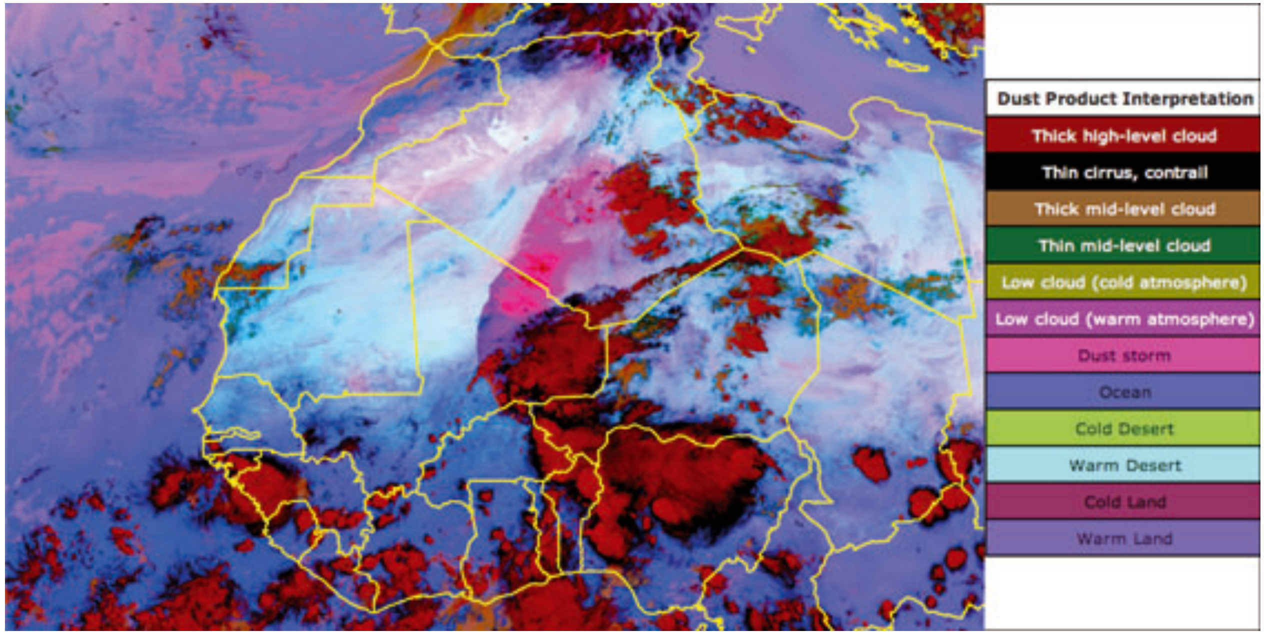
What is a haboob?

- Haboobs are a type of mesoscale dust storm produced by cold pool outflows from precipitating convective clouds (e.g. MCS).
- Cooling by precipitation produces a downdraft or downdrafts, a cold pool at the surface, and strong winds.
- The leading edge of the cold pool and strong winds is known as a gust front and, in areas where this leads to dust emissions from the surface, typically demarcates the leading edge of the haboob.



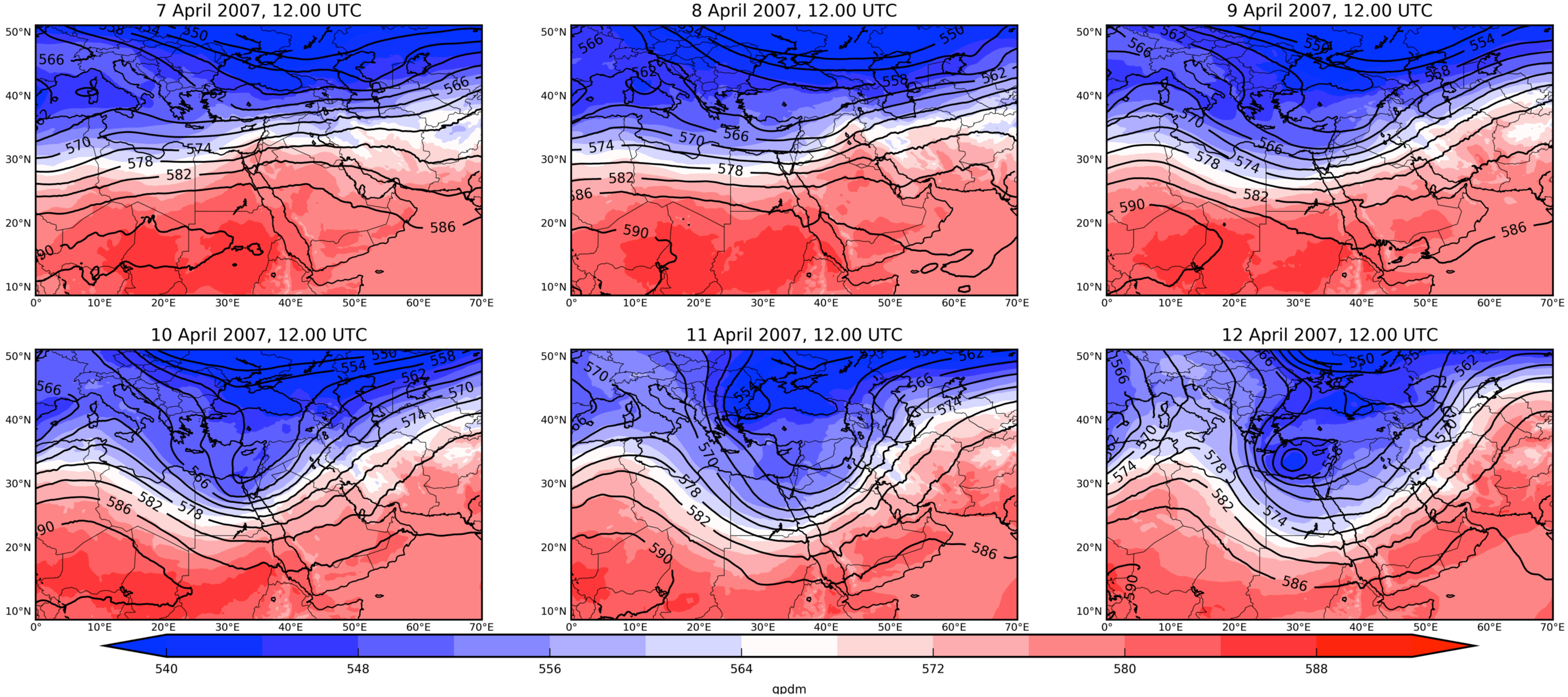


Knippertz et al. 2007



Synoptic situation during the observational campaign
ECMWF operational analysis

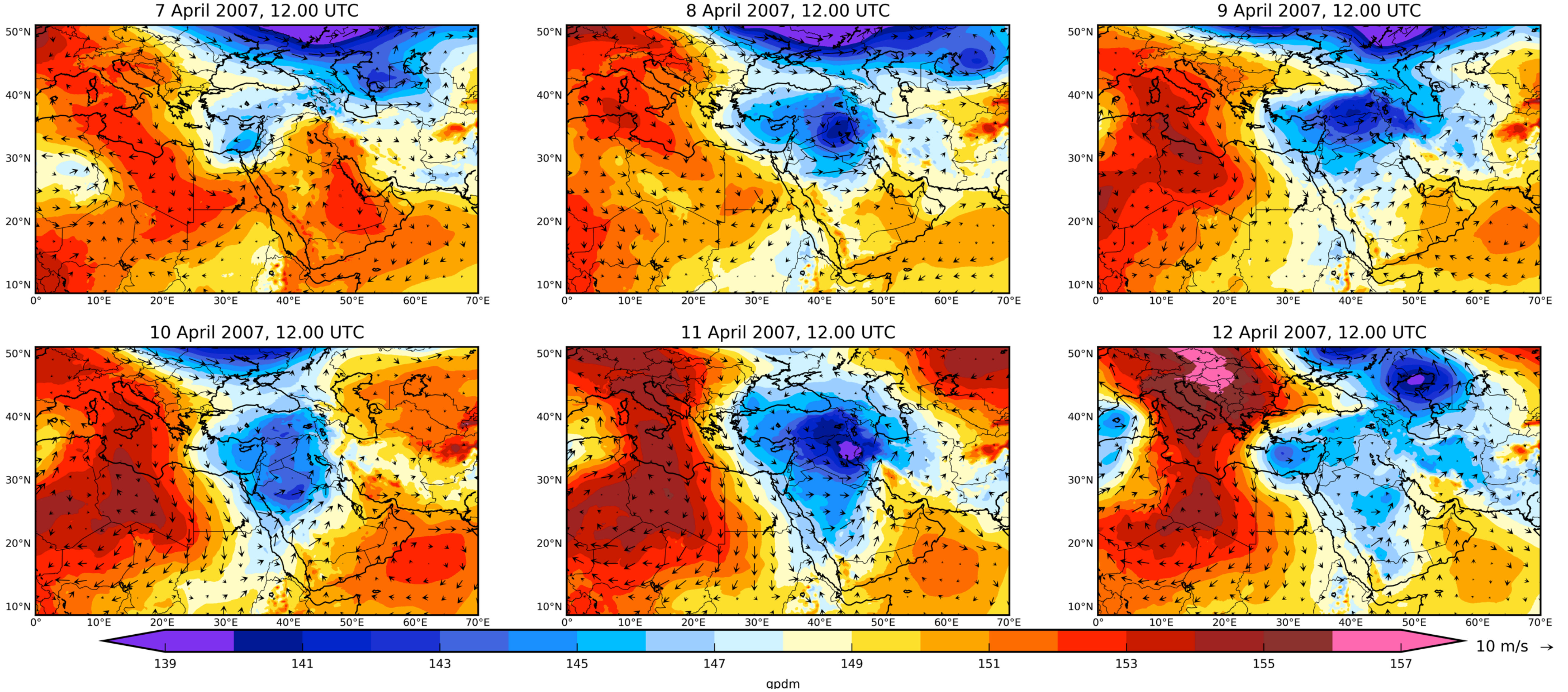
GP @500 hPa - GP @1000 hPa (color) + GP @ 500 hPa (contour lines)



Synoptic situation during the observational campaign

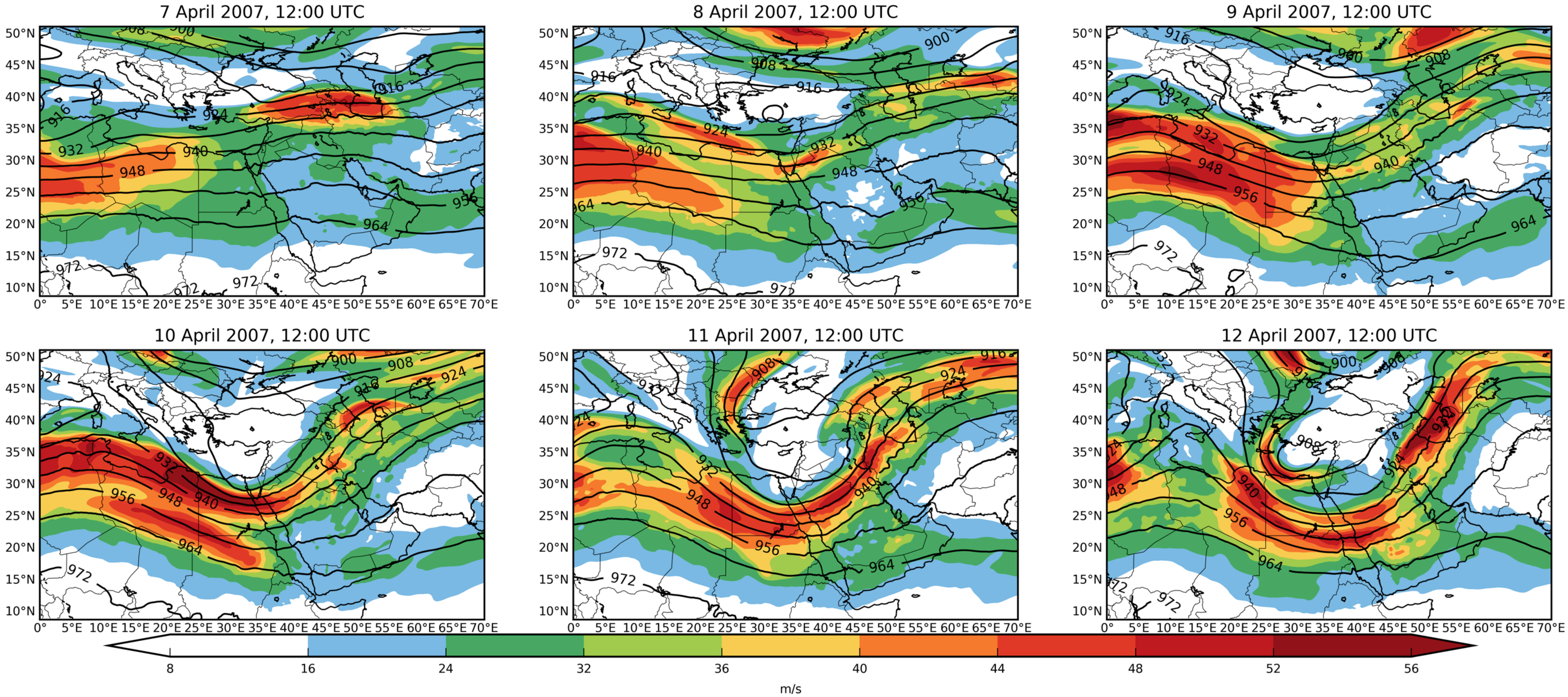
ECMWF operational analysis

GP @850 hPa (color) + Wind velocity @850 hPa (vectors)

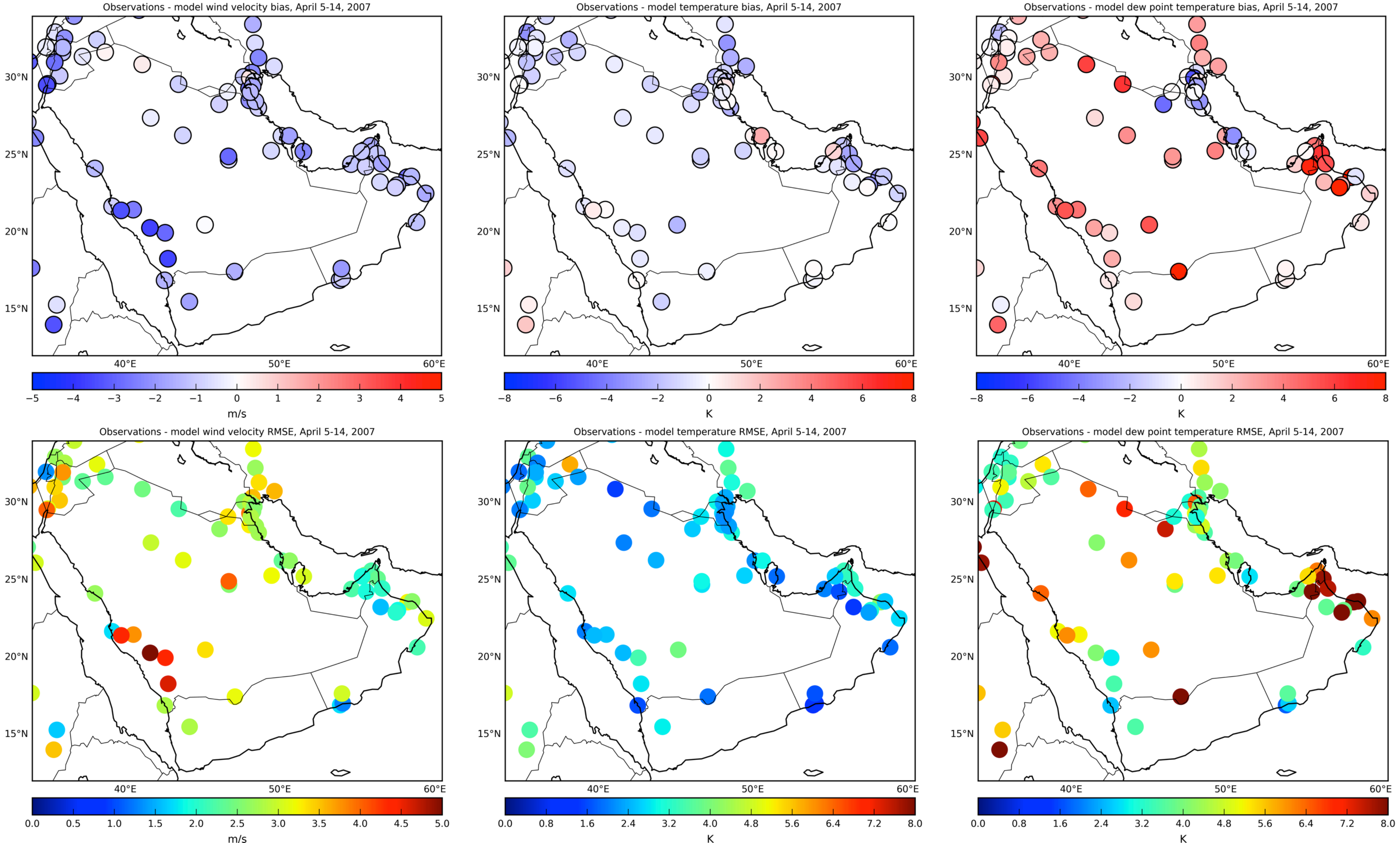


Synoptic situation during the observational campaign
ECMWF operational analysis

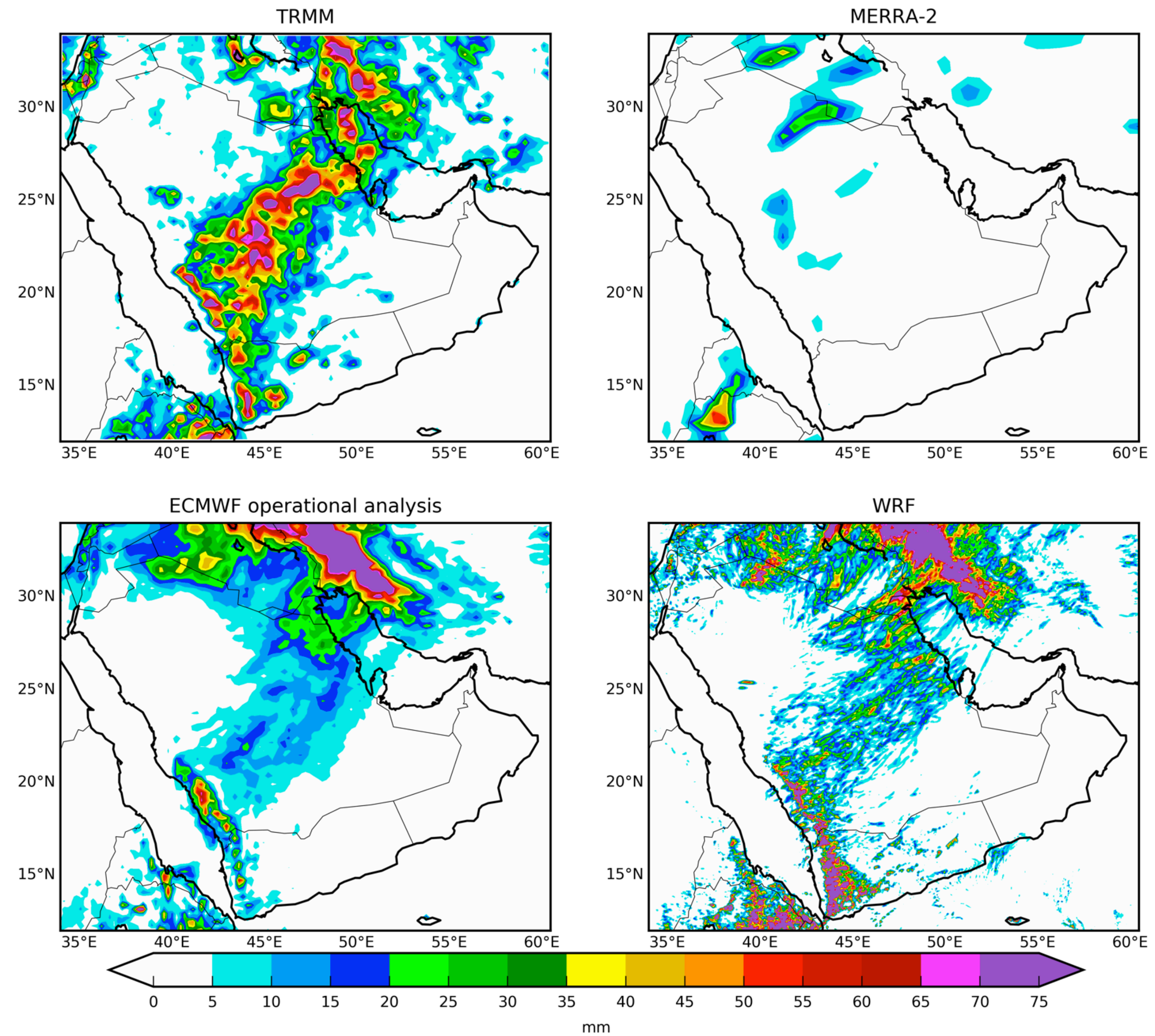
Wind velocity @300 hPa (color) + GP @300 hPa (contour lines)



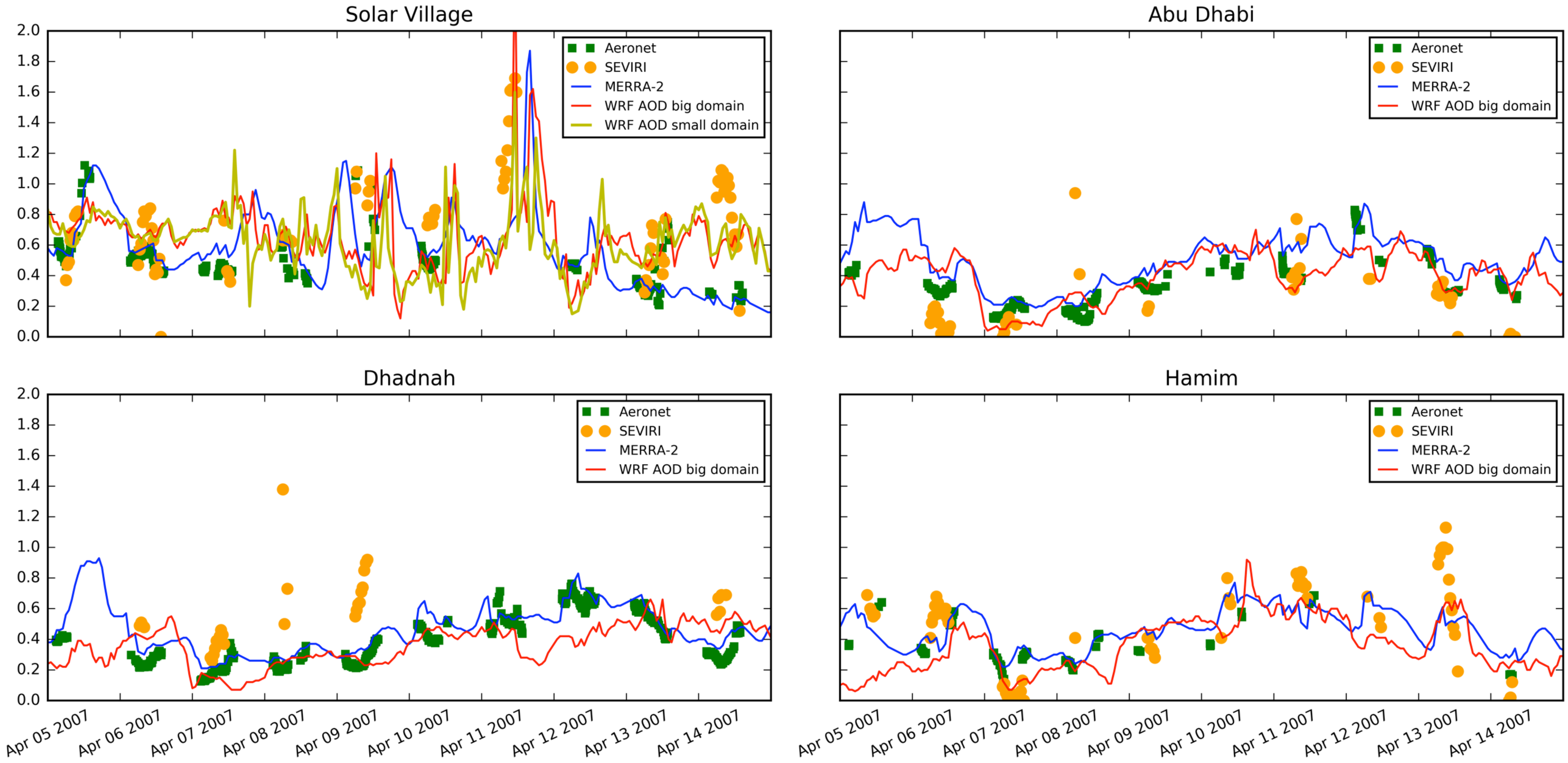
Model evaluation: bias & RMSE



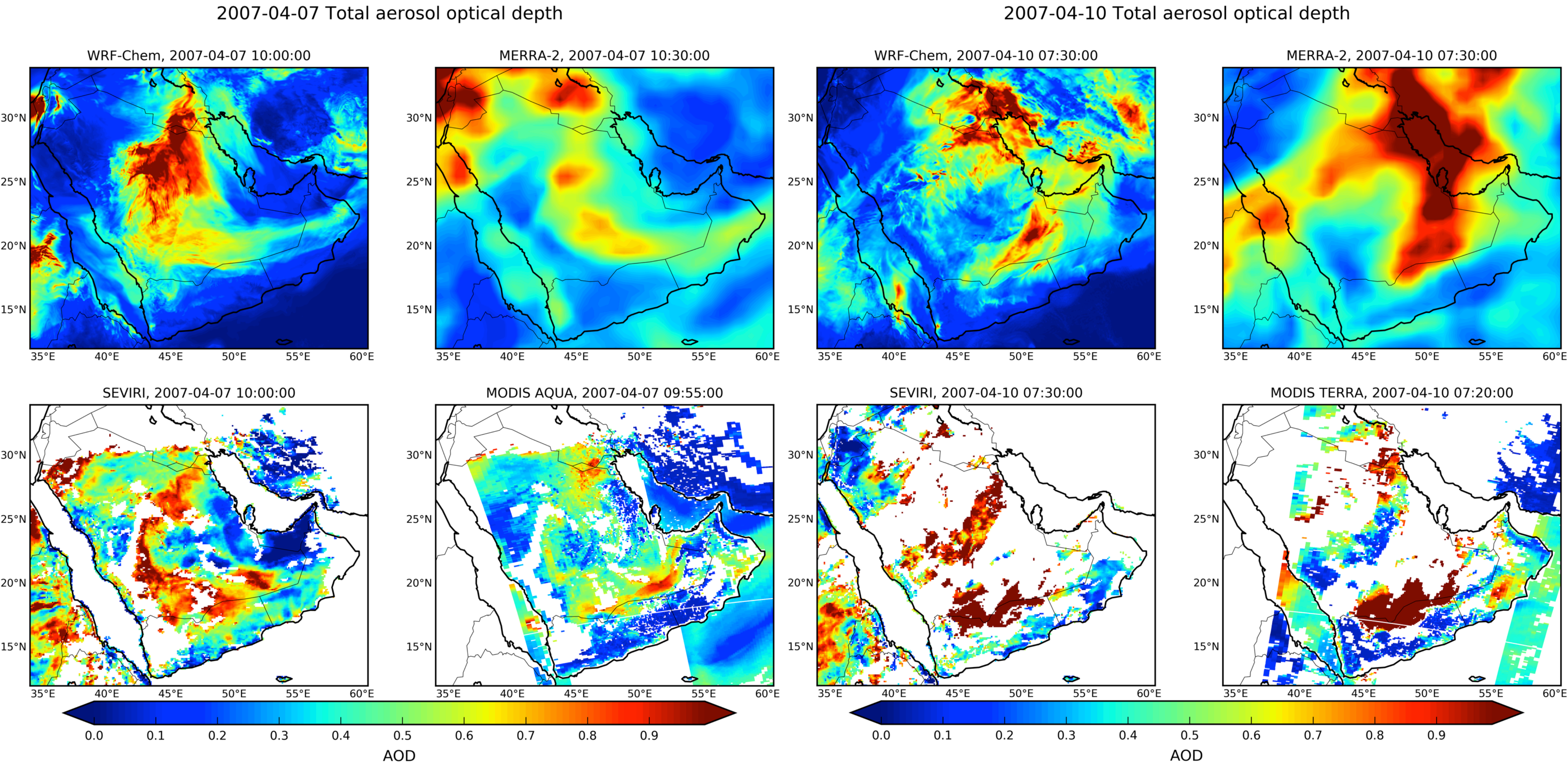
5 - 14 April 2007 accumulated precipitation



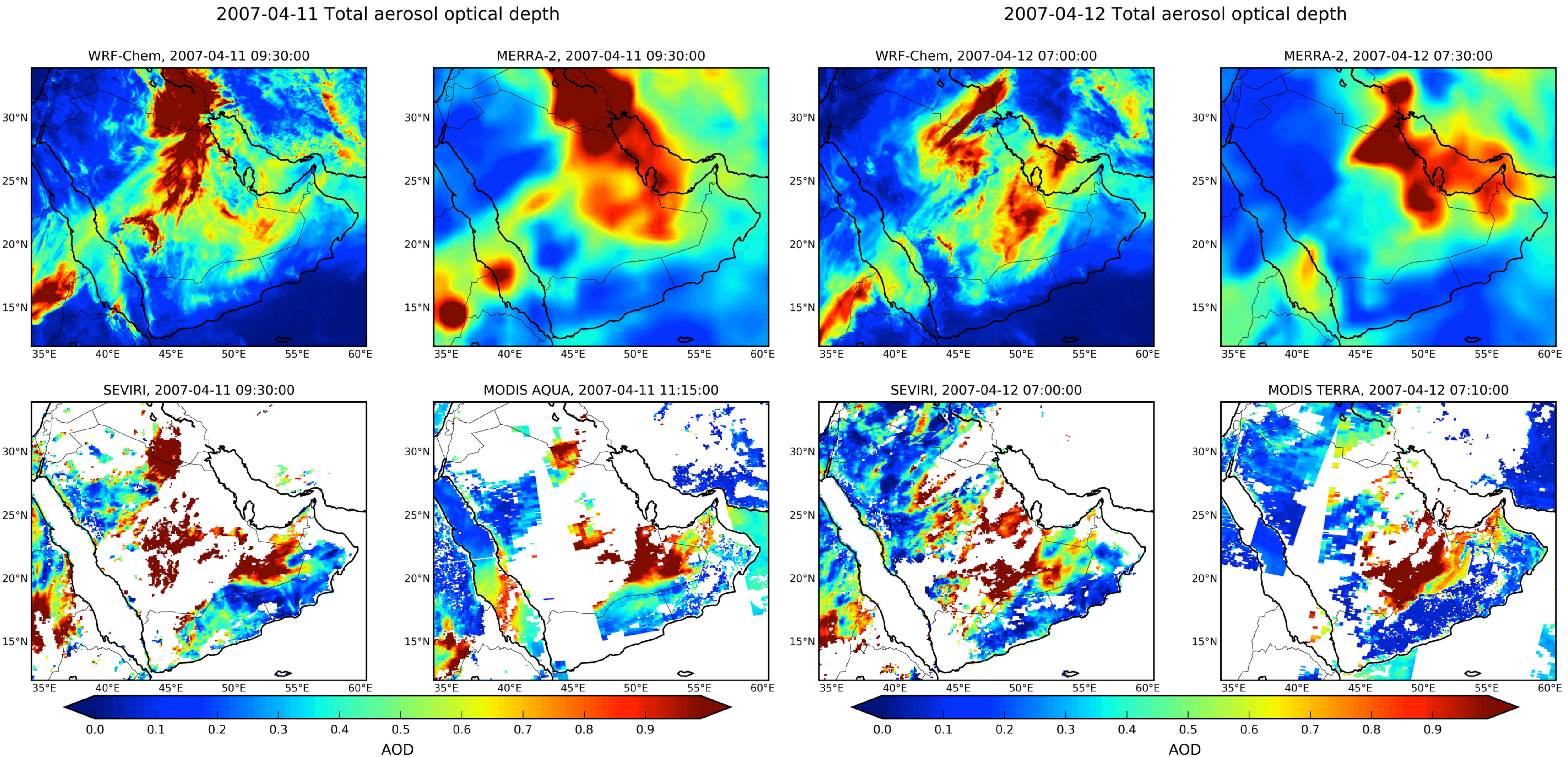
Model evaluation: AOD temporal evolution @ Aeronet sites



Model evaluation: AOD patterns



Model evaluation: AOD patterns

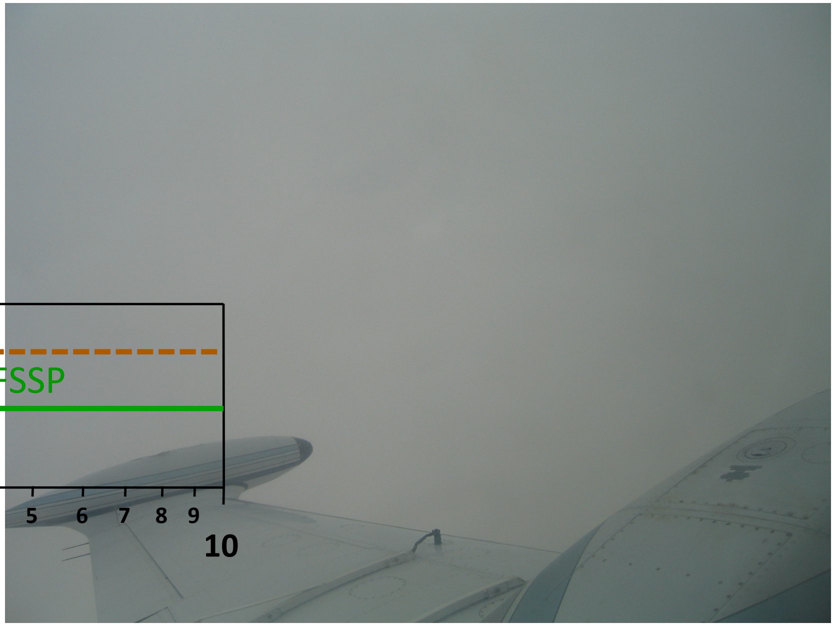


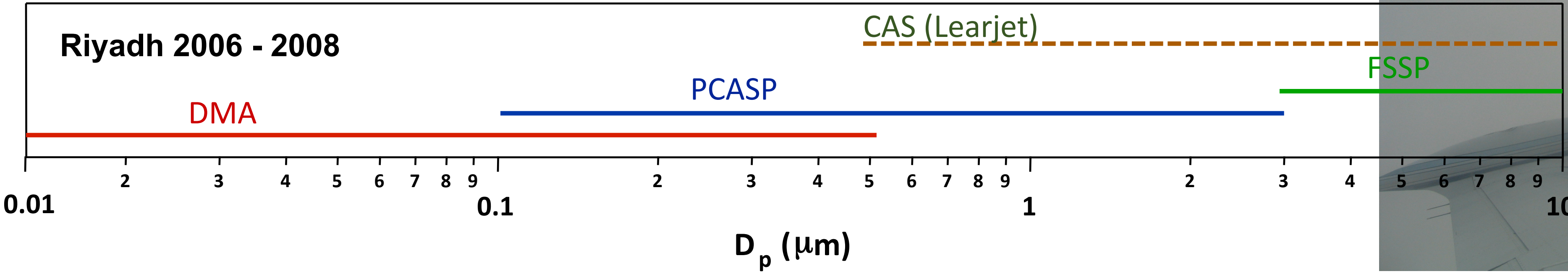
Aircraft measurements: details

- Given the small spatial extent of the aircraft trajectory (but high altitudes reached), we treat the measurements, we perform the vertical integration and treat them as column averages.
- Model vertically-integrated profiles are obtained by averaging within 1 x 1° around the flight area.
- Model results are presented separately for all aerosols and dust-only aerosols.
- The comparison against AERONET size distribution inverse product was also performed.

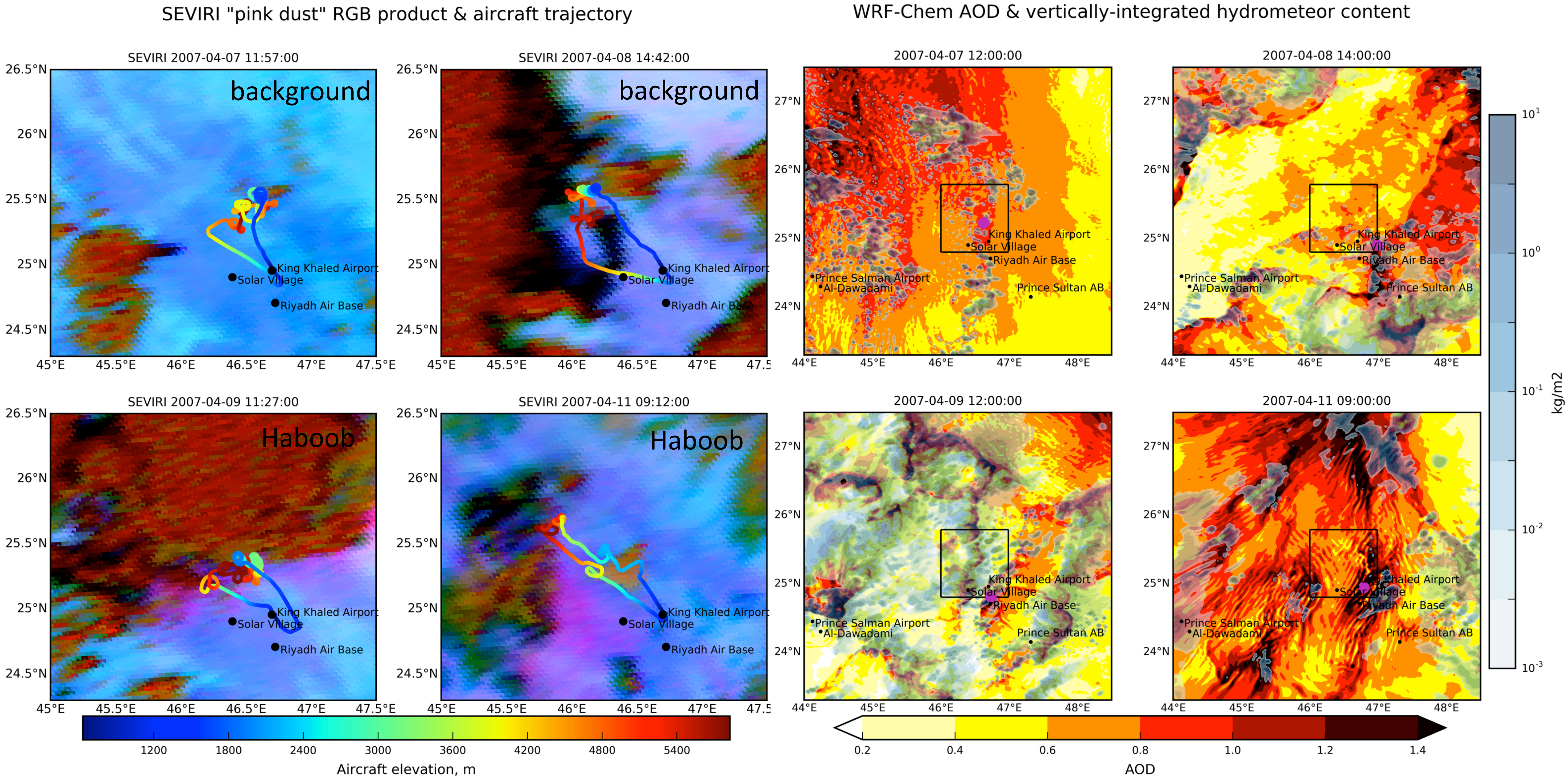
Aircraft equipment

- **Forward Scatter Spectrometer Probe (FSSP) – cloud droplets (3mm - 50mm)**
- **Passive Cavity Aerosol Spectrometer Probe (PCASP) – aerosols (0.1 to 3mm)**
- King Liquid Water Content Probe (KLWC) – cloud liquid water content
- TAMU Differential Mobility Analyzer (DMA) – aerosols (0.01mm to 0.38mm)
- **DMT Cloud Condensation Nucleus (CCN) counter**
- Arizona State University (ASU) Microanalysis Particle Sampler (MPS)
- University of Wyoming CCN counter



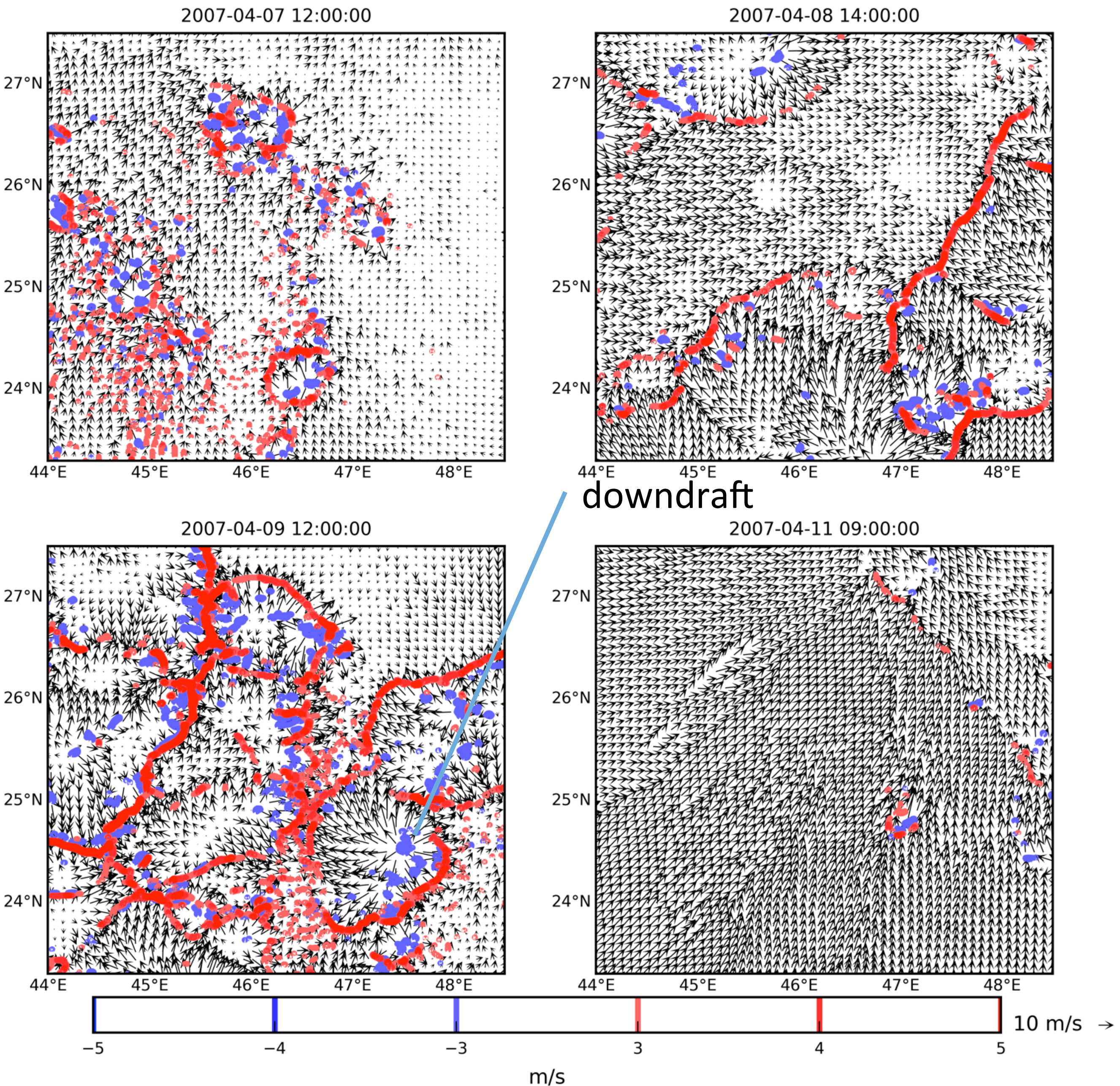


Aircraft observational cases against the model

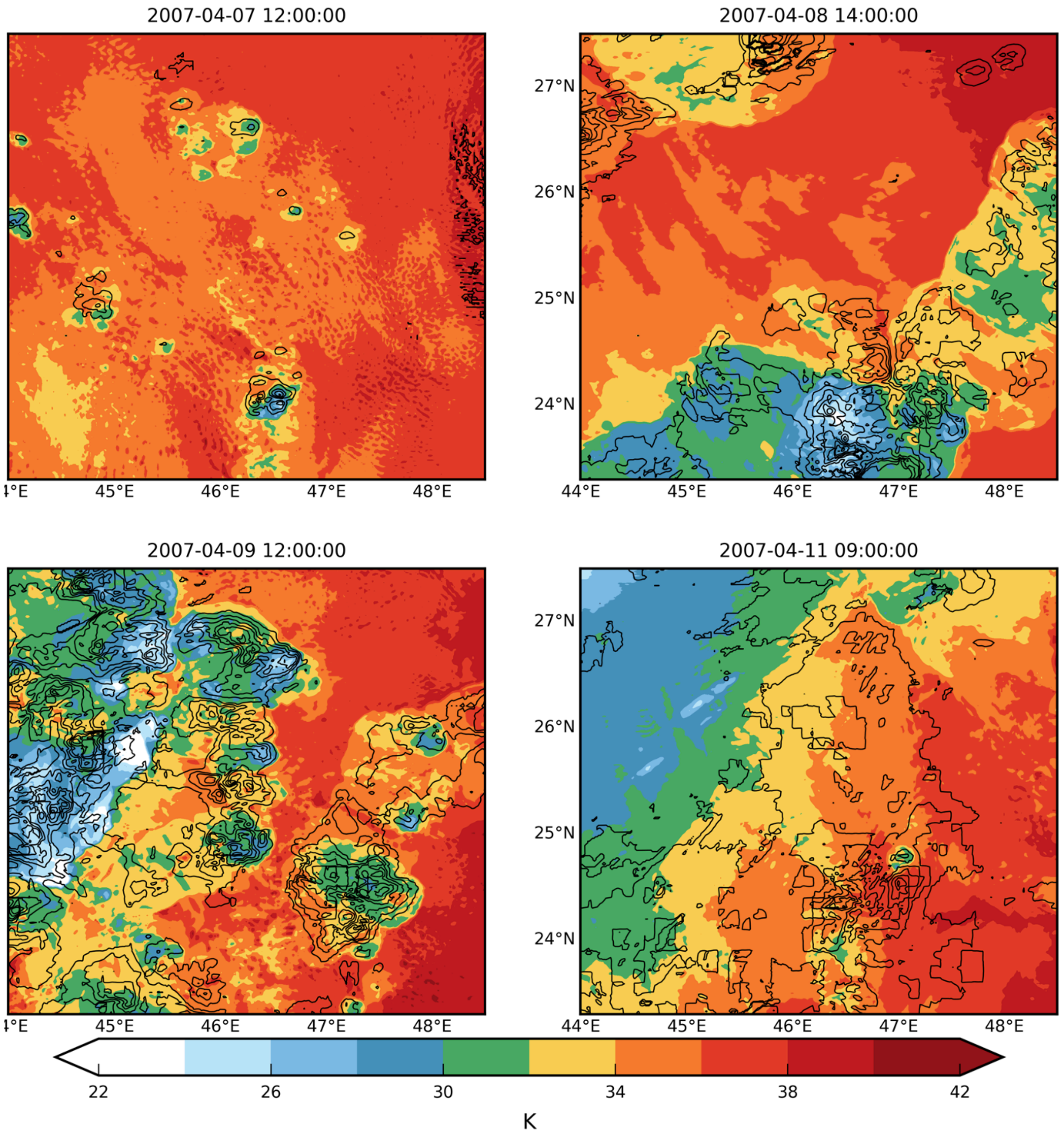


Haboobs in the model

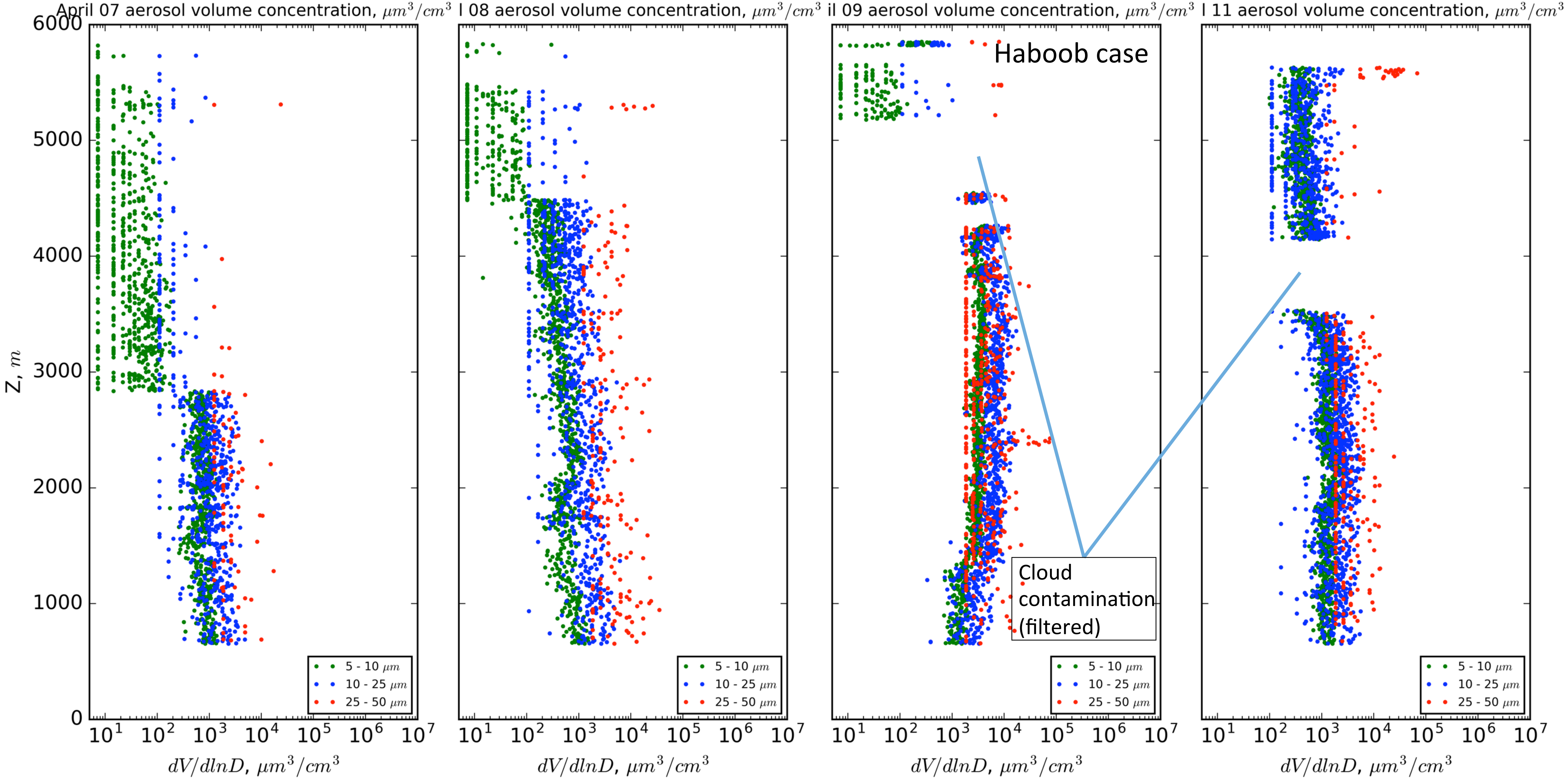
WRF-Chem surface wind & vertical velocity @ 1000 m

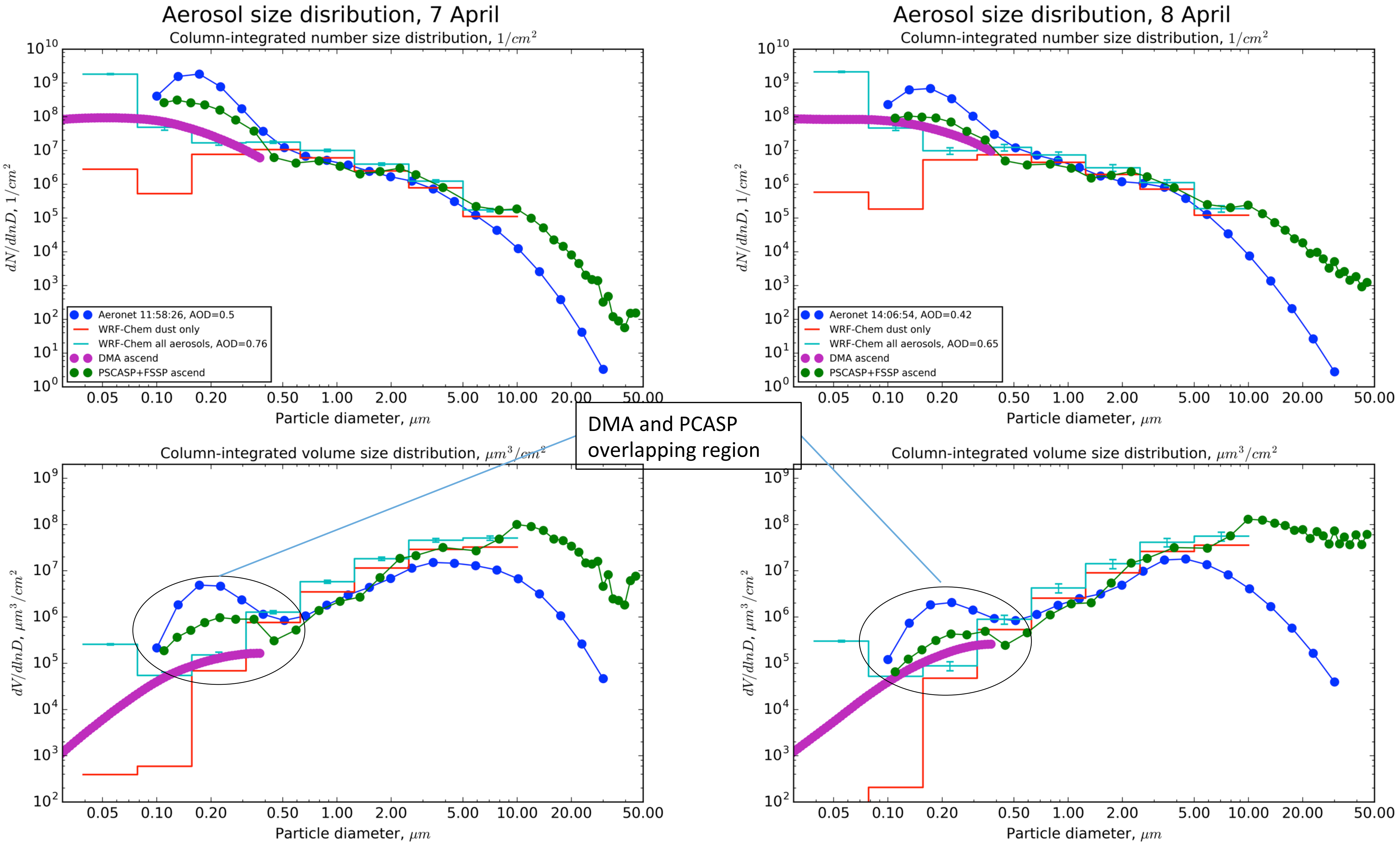


WRF-Chem 2-m temperature & dust generation

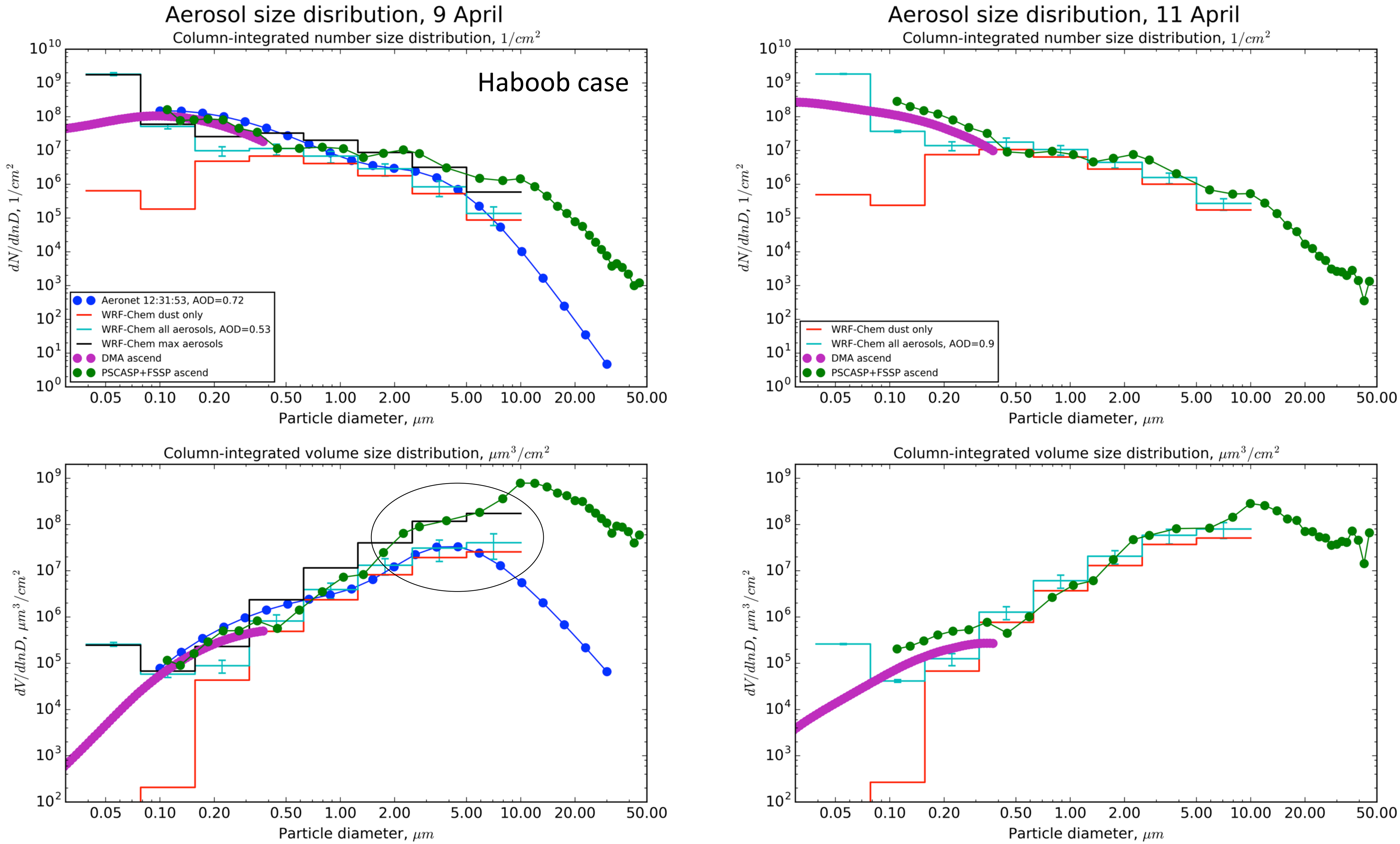


Aircraft observations: vertical profiles of aerosol volume concentrations





Aerosol size disribution, 7 April
Column-integrated number size distribution, $1/cm^2$
$dN/dlnD$, $1/cm^2$
Particle diameter, μm
Aeronet 11:58:26, AOD=0.5
WRF-Chem dust only
WRF-Chem all aerosols, AOD=0.76
DMA ascend
PSCASP+FSSP ascend
Aerosol size disribution, 8 April
Column-integrated number size distribution, $1/cm^2$
$dN/dlnD$, $1/cm^2$
Particle diameter, μm
Aeronet 14:06:54, AOD=0.42
WRF-Chem dust only
WRF-Chem all aerosols, AOD=0.65
DMA ascend
PSCASP+FSSP ascend
DMA and PCASP overlapping region
Column-integrated volume size distribution, $\mu m^3/cm^2$
$dV/dlnD$, $\mu m^3/cm^2$
Particle diameter, μm
Column-integrated volume size distribution, $\mu m^3/cm^2$
$dV/dlnD$, $\mu m^3/cm^2$
Particle diameter, μm


Aerosol size disribution, 9 April
Column-integrated number size distribution, $1/cm^2$
Haboob case
$dN/dlnD$, $1/cm^2$
Particle diameter, μm
Aeronet 12:31:53, AOD=0.72
WRF-Chem dust only
WRF-Chem all aerosols, AOD=0.53
WRF-Chem max aerosols
DMA ascend
PSCASP+FSSP ascend
Column-integrated volume size distribution, $\mu m^3/cm^2$
$dV/dlnD$, $\mu m^3/cm^2$
Particle diameter, μm
Aerosol size disribution, 11 April
Column-integrated number size distribution, $1/cm^2$
$dN/dlnD$, $1/cm^2$
Particle diameter, μm
WRF-Chem dust only
WRF-Chem all aerosols, AOD=0.9
DMA ascend
PSCASP+FSSP ascend
Column-integrated volume size distribution, $\mu m^3/cm^2$
$dV/dlnD$, $\mu m^3/cm^2$
Particle diameter, μm

Conclusions

- The meteorological variables from WRF-Chemistry simulation compare reasonably well with station measurements. The model captures the main features of convection in the Central Arabian Peninsula, producing the precipitation pattern consistent with the driving ECMWF operational analysis. Both TRMM and MERRA-2 underestimate and miss precipitation during the period of interest.

- The simulated AODs in the AERONET site locations are in good agreement with observations. The model captures most of the dust outbreaks in the central Arabian Peninsula (Solar Village) near the source region, including those that are not present in the MERRA-2 reanalysis. The background AODs in the remote sites are also well reproduced.

- The model large-scale AOD patterns across Arabian Peninsula are consistent with the remotely sensed SEVIRI & MODIS AOD and MERRA-2 reanalysis. However, some of the mesoscale dust outbreaks in Southern Arabian Peninsula are missed.

- The aerosol size distribution in the model is generally in good agreement with the aircraft observations and the AERONET inversion product. Both WRF-Chem and AERONET underestimate the coarse mode especially during the strong dust events in comparison with the aircraft observations. However, model results are in a better agreement with observations.

- Overall, the modeled size distribution is relatively stable in our case-study as we sample it close to the dust source with a fixed emission size distribution.