Impact of Global Warming on Regional Climate over the Arabian Peninsula

Prof. Georgiy Stenchikov

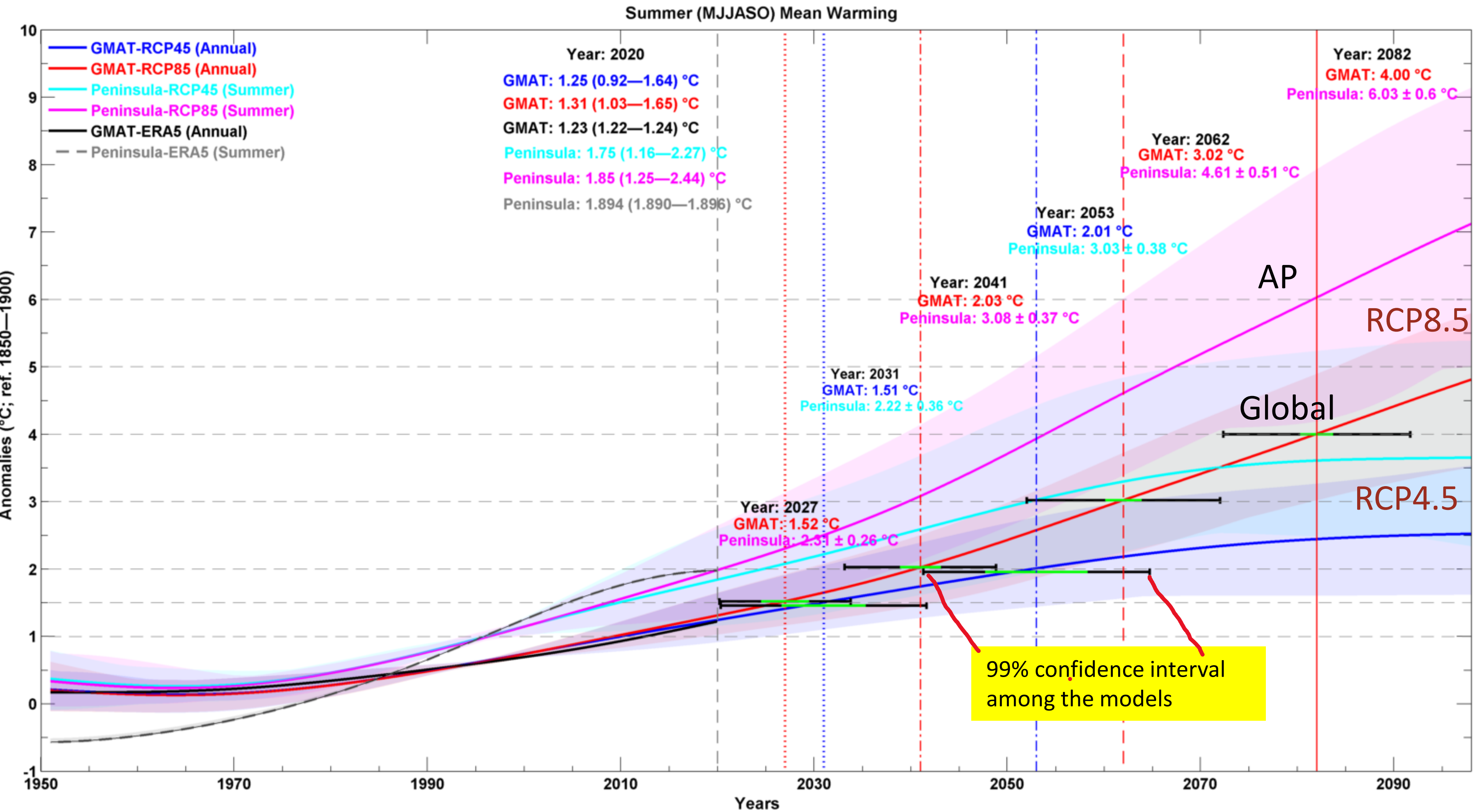
Earth Sciences and Engineering Program

Division of Physical Sciences and Engineering, KAUST

- Focus: Regional climate change, Climate feedbacks, Dust effect on climate and air quality – this is my group research effort
- Motivation: The pace of warming in the Middle East is higher than average over the Globe. The regional climate is more challenging to predict than global because of the nonlinear effect of circulation and desired high spatial resolution. New high-resolution predictive methods are required to produce a reliable regional climate forecast suitable for planning and adaptation purposes
- Objective: We evaluate the mechanisms of the regional climate sensitivity in the Middle East. For this we consider the observed regional impact of the 1991 Pinatubo aerosol forcing and quantify the impact of the regional dust aerosol forcing. I also introduce a coupled regional research tool we developed for this purpose

Regional Warming (with respect to pre-industrial 1850-1900) over the Arabian Peninsula (AP) is 30% faster than average over the Globe

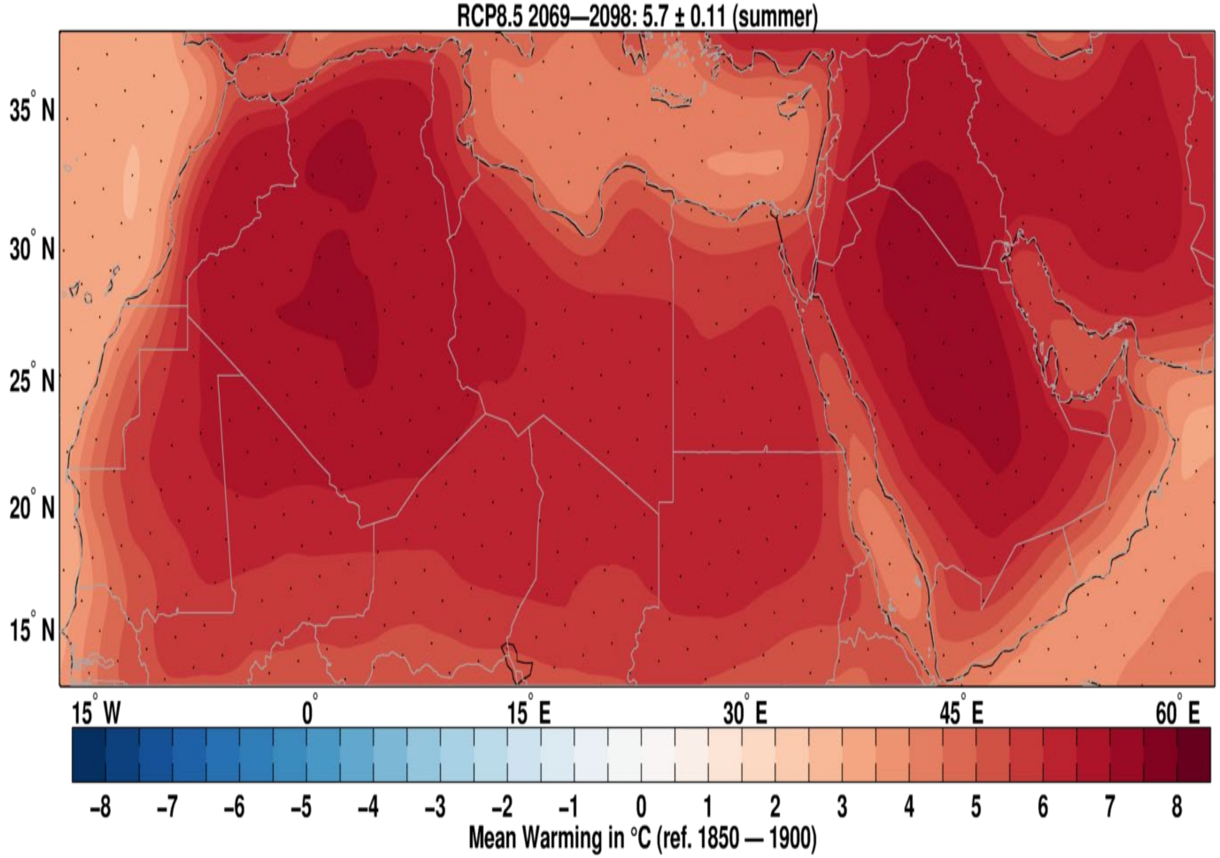
The AP and other desert regions are more sensitive to radiative forcing than the Globe



21 Member CMIP5 Model Ensemble Prediction for the 21st Century

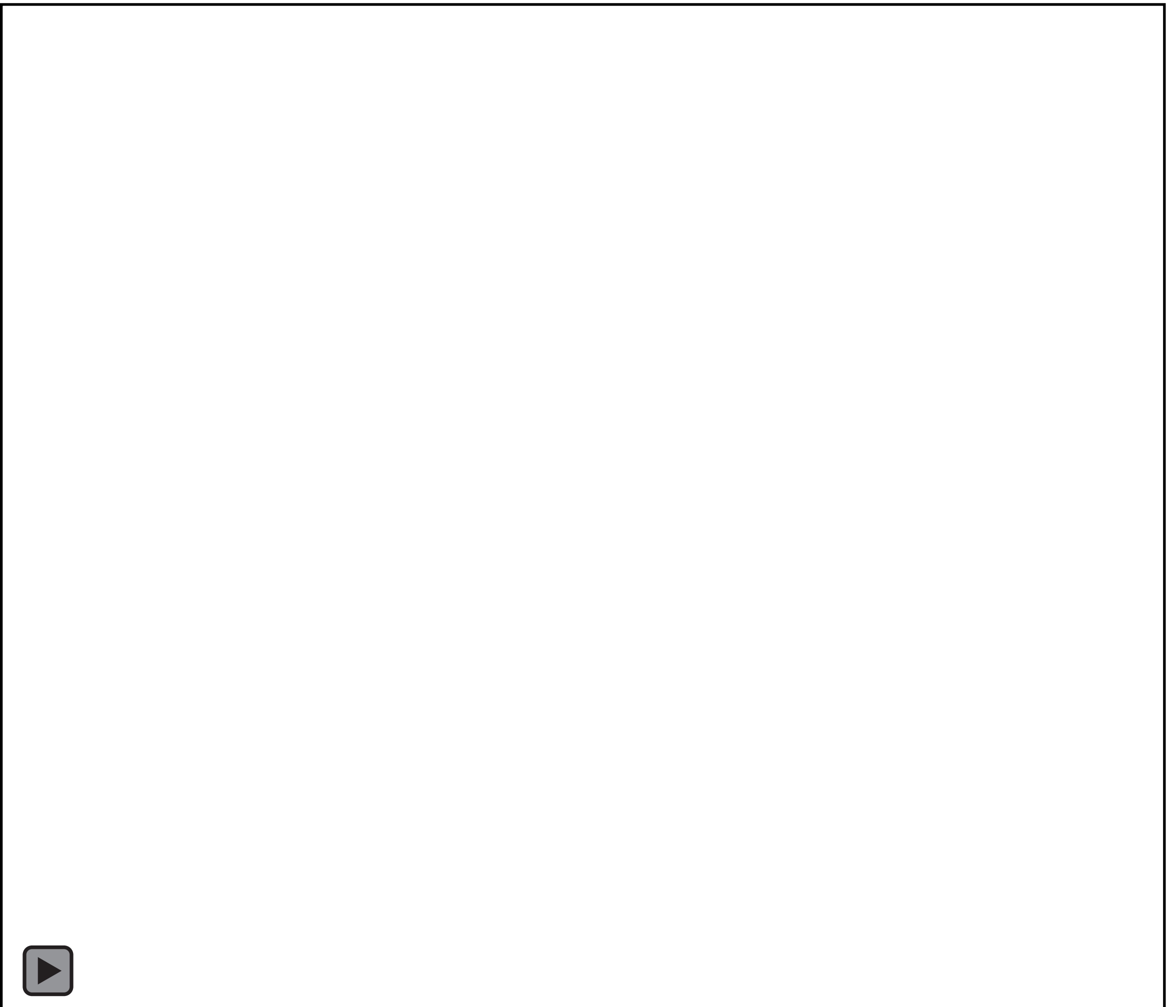
Spatial Distribution of Projected Warming in 2100

- The interior of the Arabian Peninsula warms faster than the coastal areas due to the effect of internal water bodies Red Sea, Arabian Gulf, and Mediterranean Sea



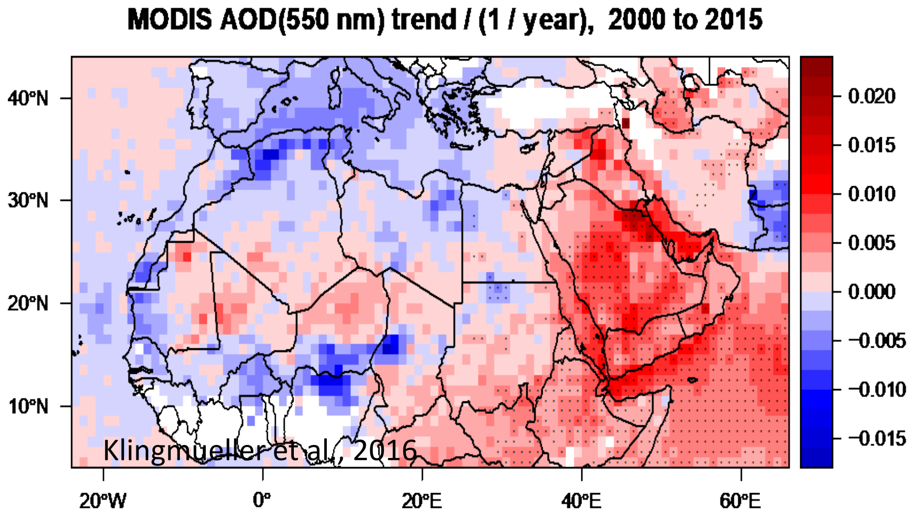
Temperature Anomalies for 2069-2098 with respect to pre-industrial mean 1850-1900

The Middle East contributes 20-30% to global dust emissions
Dust affects Climate and Air Quality

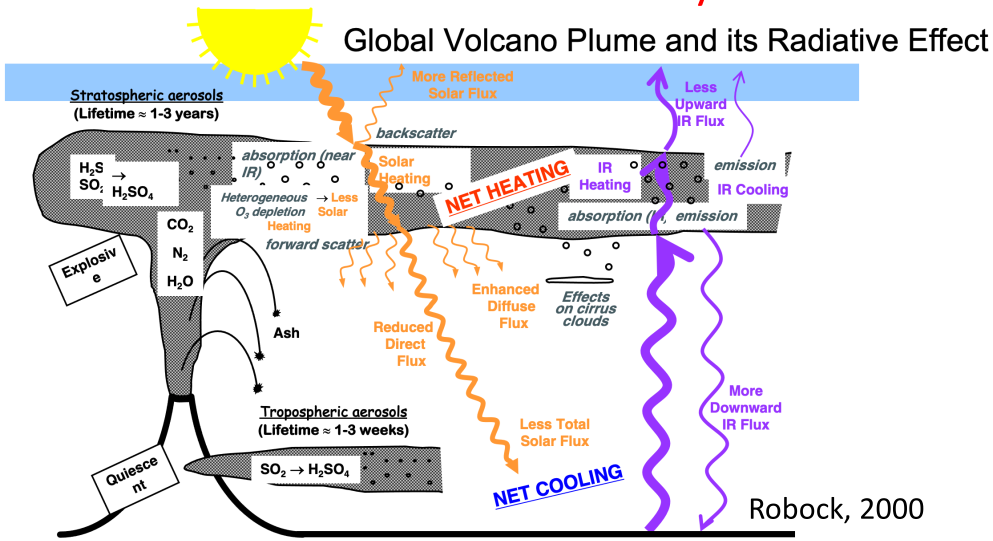


- Dust storms originating in the Middle East strongly affect the regional radiation budget, cyclogenesis, atmospheric circulation, and air quality.
- Dust also severely affects the regional seas, the Red Sea and the Arabian Gulf.
- The mean dust shortwave radiative (SW) forcing over the southern Red Sea is the largest in the world, reaching 60 W/m^2.
- Dust provides nutrients for marine microorganisms.

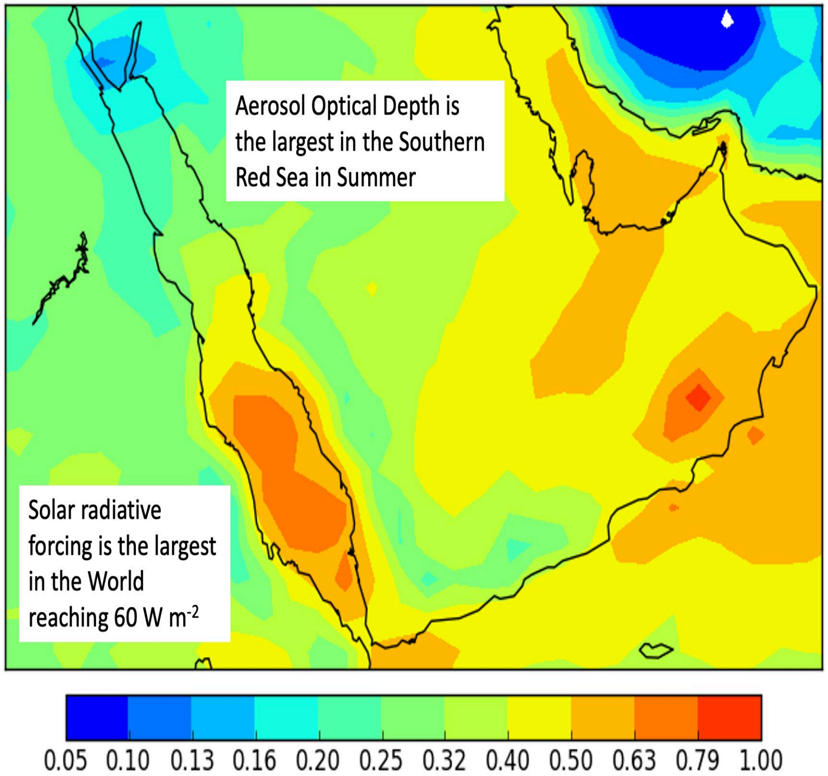
Dust is raising



Pinatubo Cooled the Planet by 0.5 C



Dust absorbs SW Radiation & cools the Sea



Middle East Cooling was Much Higher than Global

We Developed Coupled Ocean-Atmosphere Regional Modeling System to better understand

- Why the Middle East has high Regional climate sensitivity
- What is the regional effect of locally generated radiative forcing
- How internal seas could be affected by radiative forcing

Osipov and Stenchikov, JGR-Oceans 2017 & 2018

Pinatubo case:
Mie + Sato optical depth and effective radius (Sato, 1993 & Stenchikov, 2006)

Dust case:
Mie, T-matrix and geometric optics + SEVIRI optical depth (Osipov, 2015, Brindley, 2015)

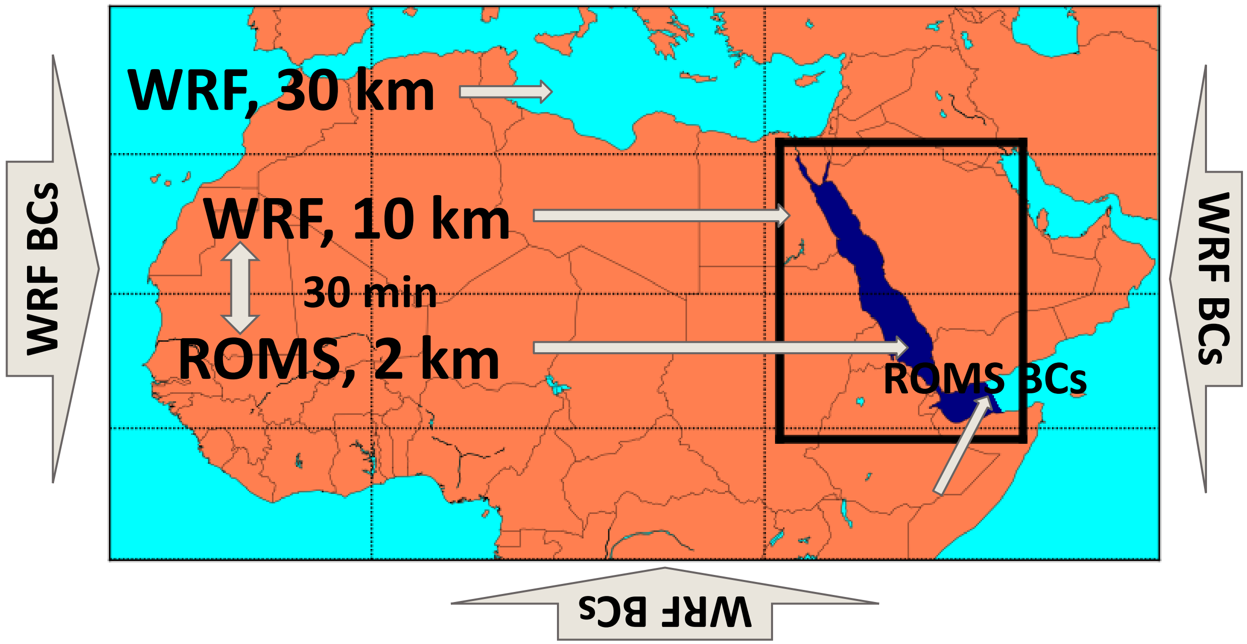
Spectral optical properties
$\varepsilon(\lambda)$, $\omega(\lambda)$, $g(\lambda)$

Atmosphere
(WRF, RRTMG)

30 min

Ocean
(ROMS)

WRF BCs

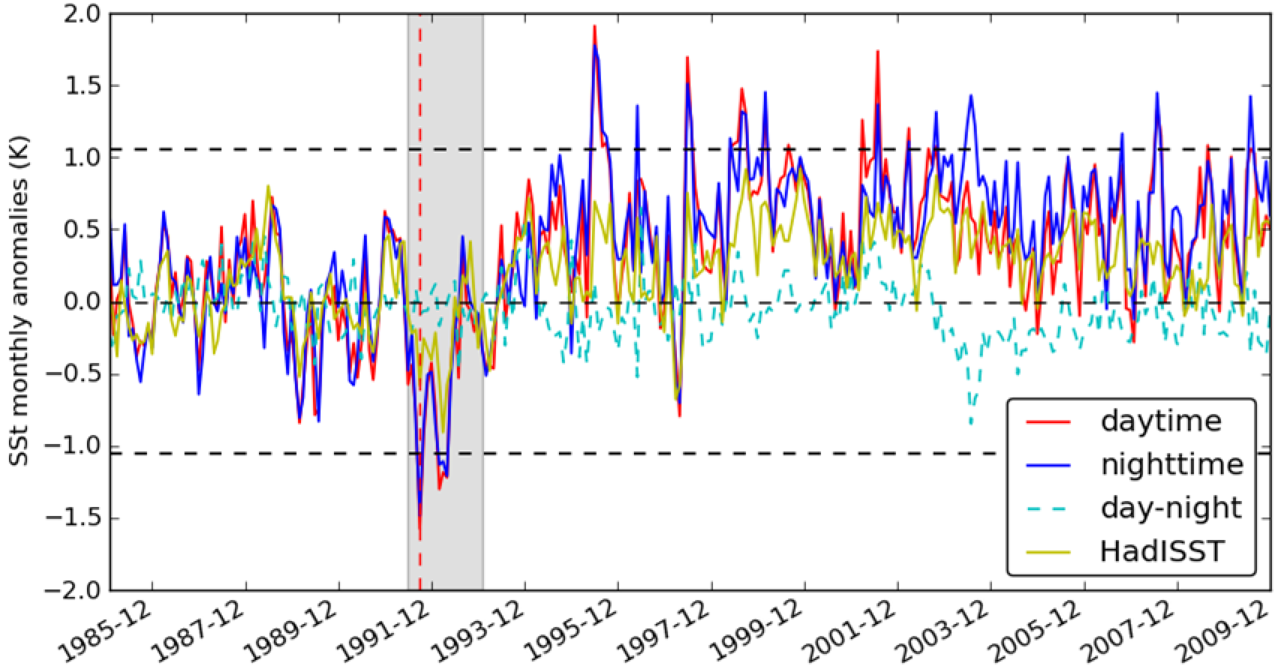


Framework:
A Coupled Ocean Atmosphere Wave Sediment Transport Modeling System (COAWST)

Atmosphere:
Weather Research and Forecasting Model (WRF)

Ocean:
Regional Ocean Modeling system (ROMS)

The observed Red Sea surface temperature decreased more than 1C

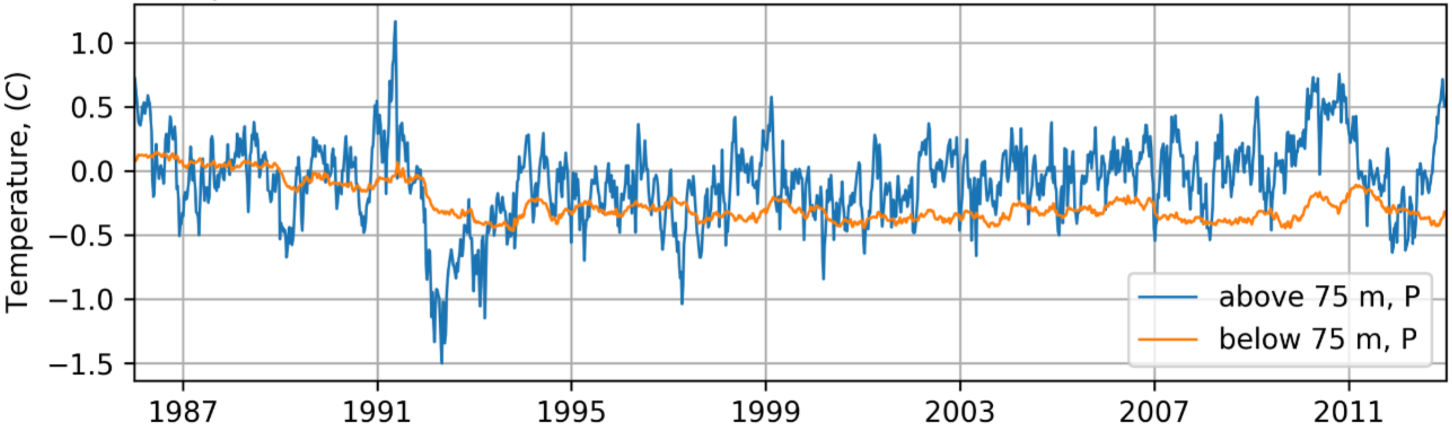


Healthy coral reef

Reef bleaching after Pinatubo

Genin et al., 1995

The simulated Red Sea Temperature Anomaly well replicates the observations



Atmospheric response to Volcanic Forcing

Total cooling = Perturbed run minus 1987-1991 DJF climatology

Dynamical response is well captured by model due to imposed "observed" large scale circulation

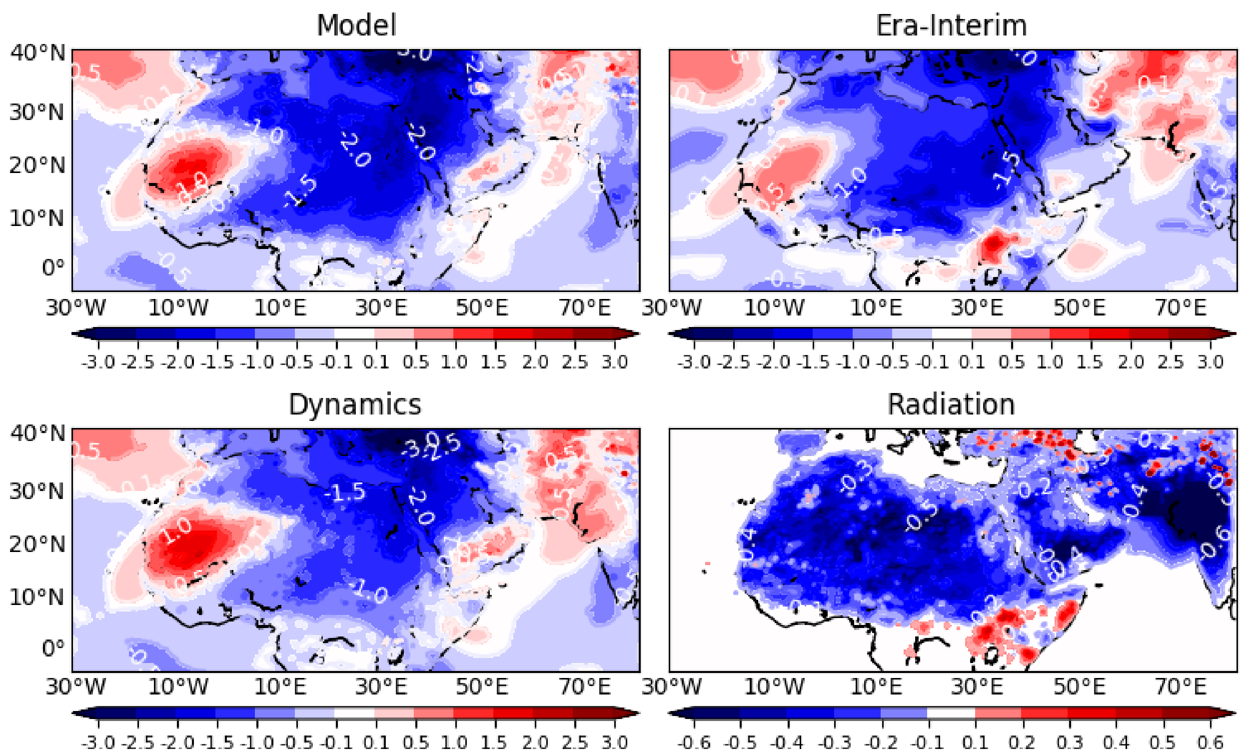
Severe 1991 & 1992 DJF cooling of -1 and up to -2.5 C

Dynamical cooling = Control run minus climatology

Radiative cooling = Perturbed minus Control run

Dynamical cooling is 2-3 times bigger than direct radiative cooling by volcanic aerosol.

Surface air temperature (SAT) anomaly
1991 & 1992 DJF mean

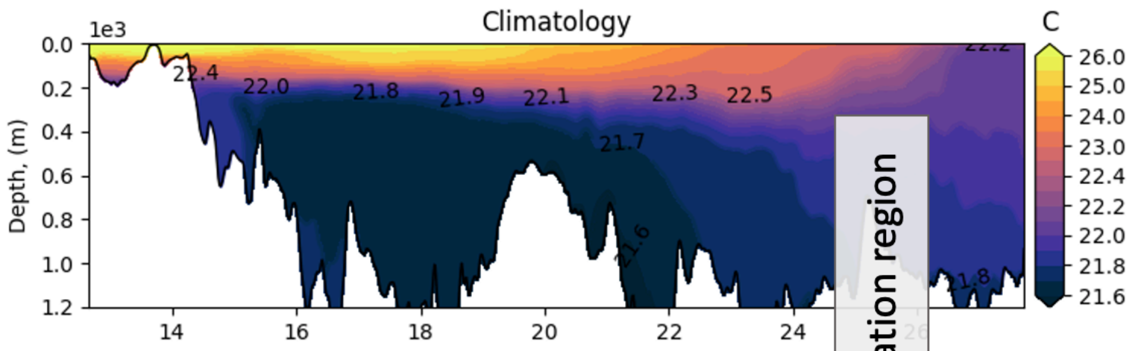


	Red Sea	Global ocean
SST anomaly peak	-1 C	3 times smaller
Main forcing	LH & SH	Solar dimming (SW)
Heat uptake time scales	0.5 years	15 year
Overturning anomaly	50%	10% (Atlantic Ocean)

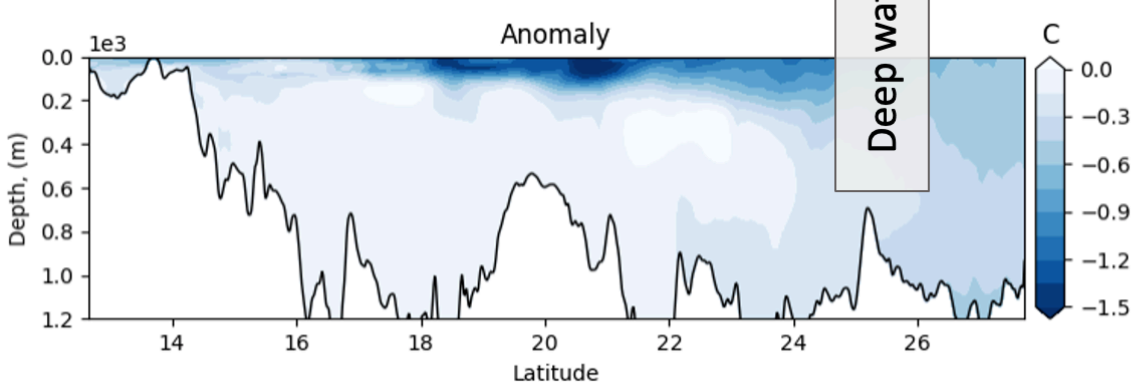
Volcanic Forcing Strengthens Red Sea Overturning by 50%

Weakly stratified water column and strong atmospheric cooling result in increased deep water formation and strengthening of the overturning circulation

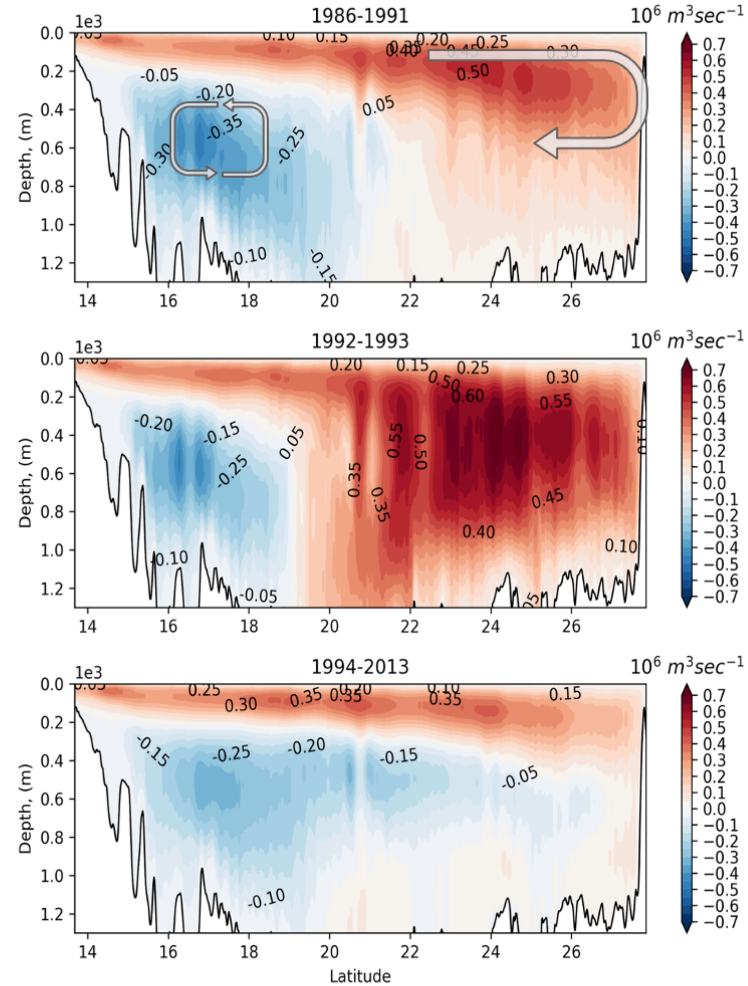
Θ, winter (DJF) climatology



Θ, 1992 winter (DJF) anomaly wrt climatology

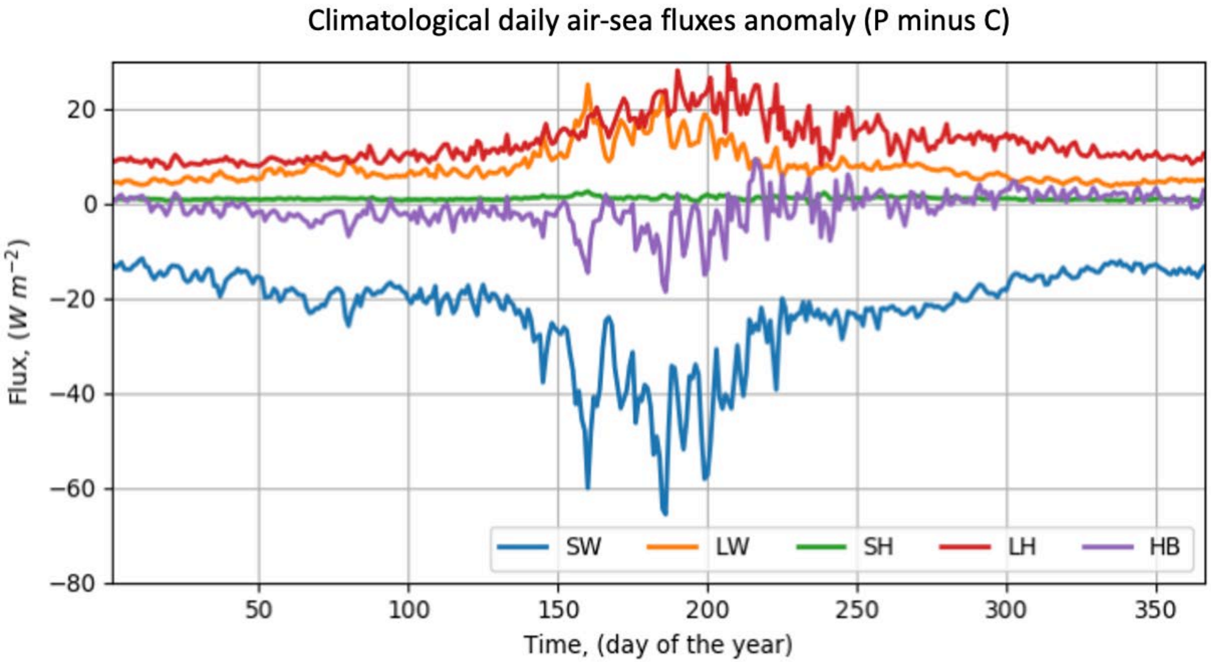


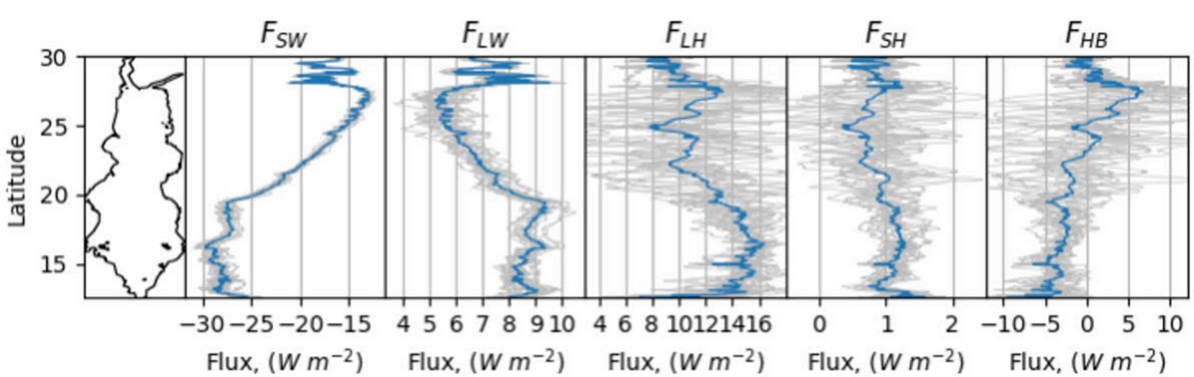
Overturning stream function response



Red Sea overturning time scales are 10 and 40 years for the 1st and 2nd cells, respectively

Dust radiative Impact on the Red Sea





- Heavy climatological dust loading over southern Red Sea during JJA
- Surface radiative SW cooling up to -60 Wm^{-2} and LW warming up to 20 Wm^{-2}
- SST response reaches -0.5 K
- Annual heat and freshwater budgets reduction by 3.2 Wm^{-2} and 0.086 m $year^{-1}$.
- Dust slows down the Red Sea overturning circulation by 5-10%

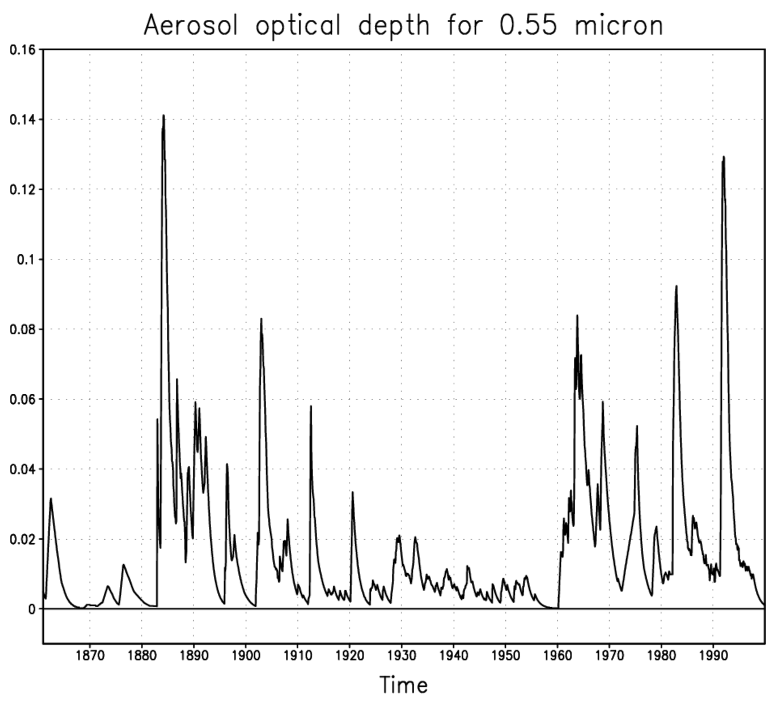
SUMMARY

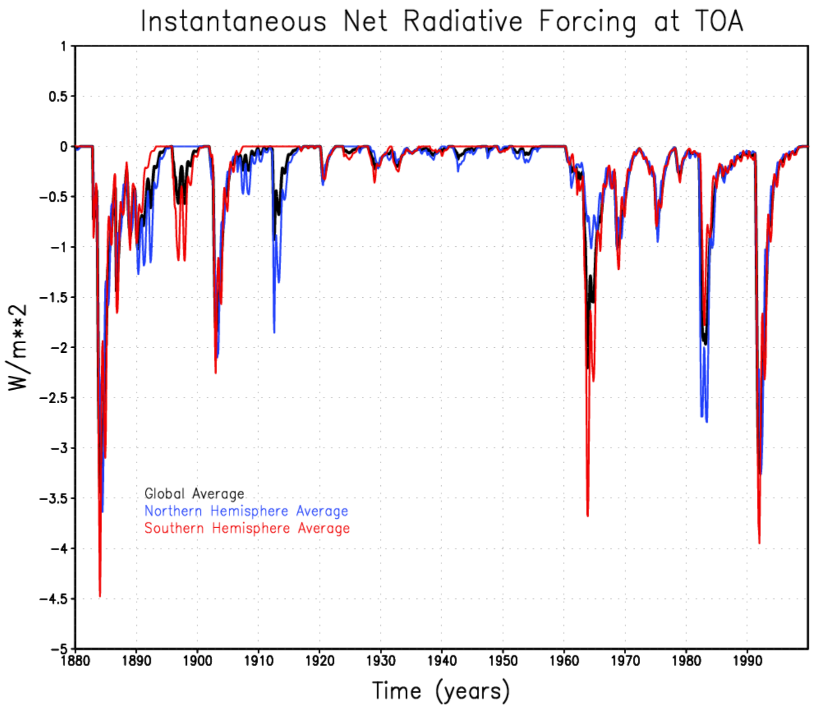
- The Middle East regional climate sensitivity is significantly higher than average over the Globe
- Regional Warming depends on the emission scenario but, in the worst case, could exceed 5 K in the central Arabian Peninsula by 2100. The spatial distribution of predicted warming indicates the important role of regional seas
- Coupled WRF-ROMS regional ocean-atmosphere model is a proper tool to tackle the Middle East regional climate. It calculated exceptionally well the impact of Pinatubo and dust radiative forcing on the Middle East
- Dust-induced regional radiative forcing develops an important climatological impact on the surface air temperature, SST, and sea circulation and has to be incorporated in predictive models
- The changes in atmospheric circulation patterns associated with the phase of Arctic Oscillation, Indian Monsoon, Atlantic SST, position of ITCZ, and ENSO contribute to regional sensitivity of the Middle East climate and produce even stronger climate signature than direct radiative forcing
- Red Sea, Arabian Gulf, and the Mediterranean Sea are affected by global warming and have to be interactively included in a coupled regional systems for future climate assessments

Climate Projections using Fine-Resolution GLOBAL MODEL

This study was conducted in the scope of the Assessment of Climate Change Impacts on Water Resources and Socio-Economic Vulnerability in the Arab Region supported by the United Nations Economic and Social Commission for Western Asia (ESCWA)

Volcanic Radiative Forcing

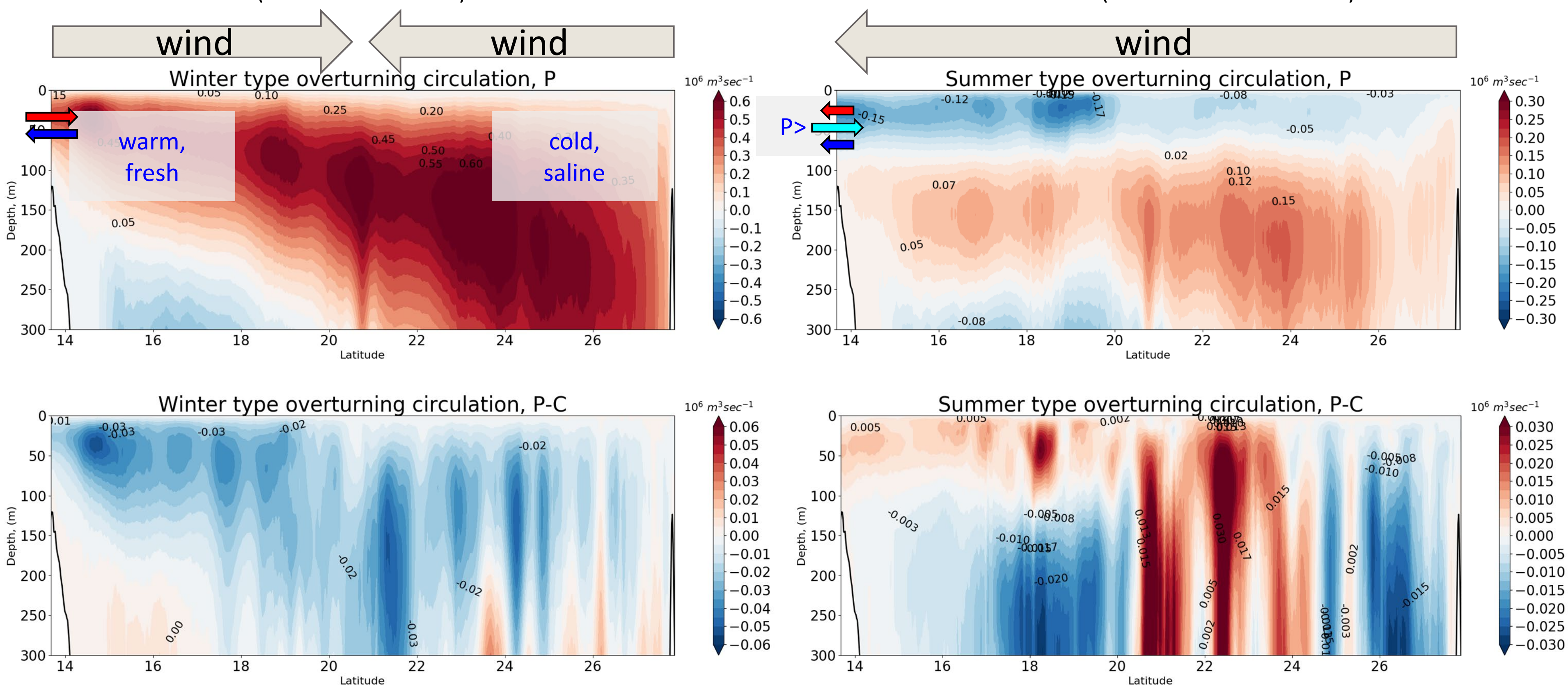




Dust Forcing Slows Down the Overturning

October-May,
driven by thermohaline forcing
(inside the Red Sea)

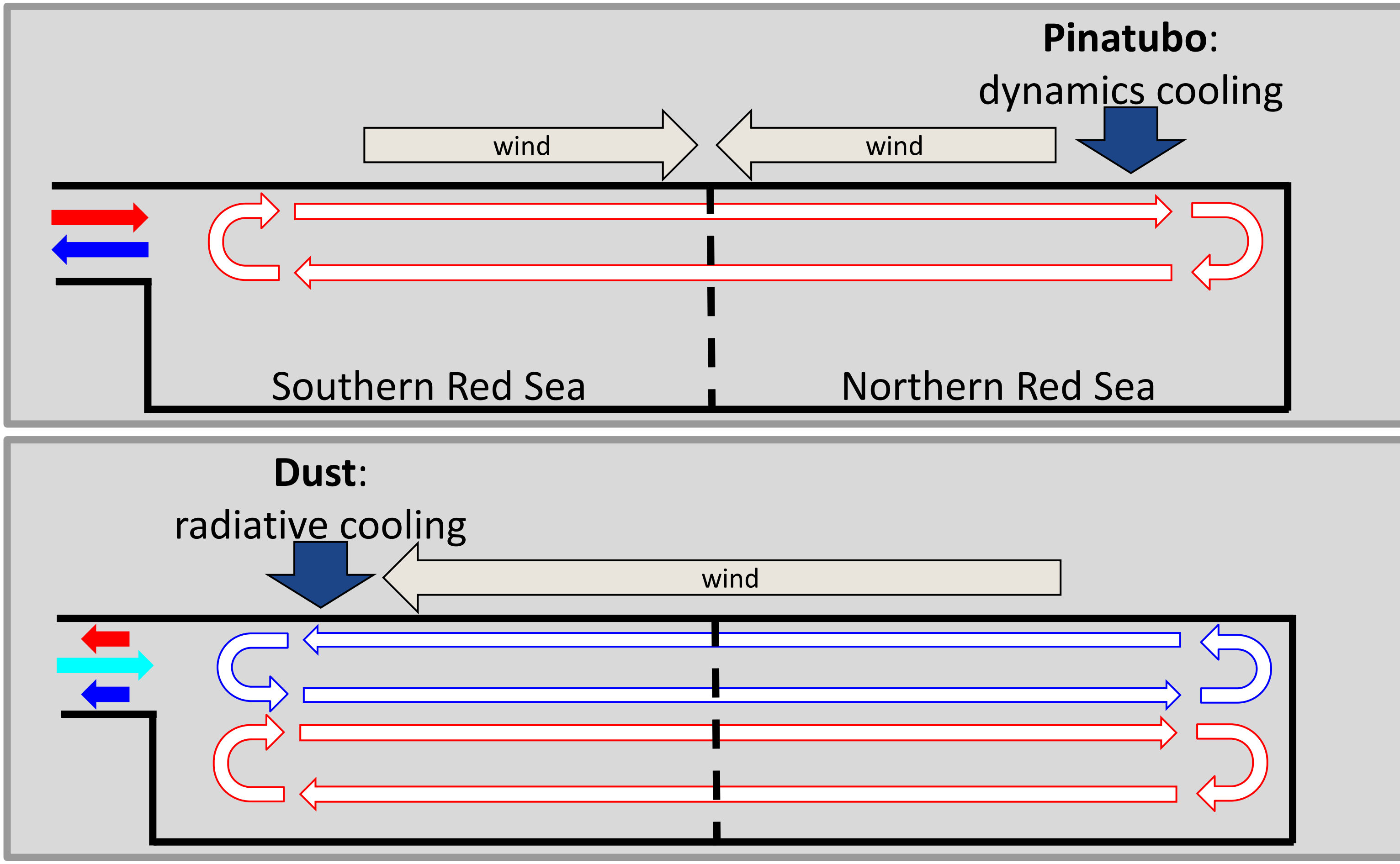
June-September,
driven by local wind forcing and
GAIW intrusion (outside of the Red Sea)



Red Sea circulation responds differently to dust and volcanic radiative forcings

Winter:

Summer:



Conclusions: Pinatubo case

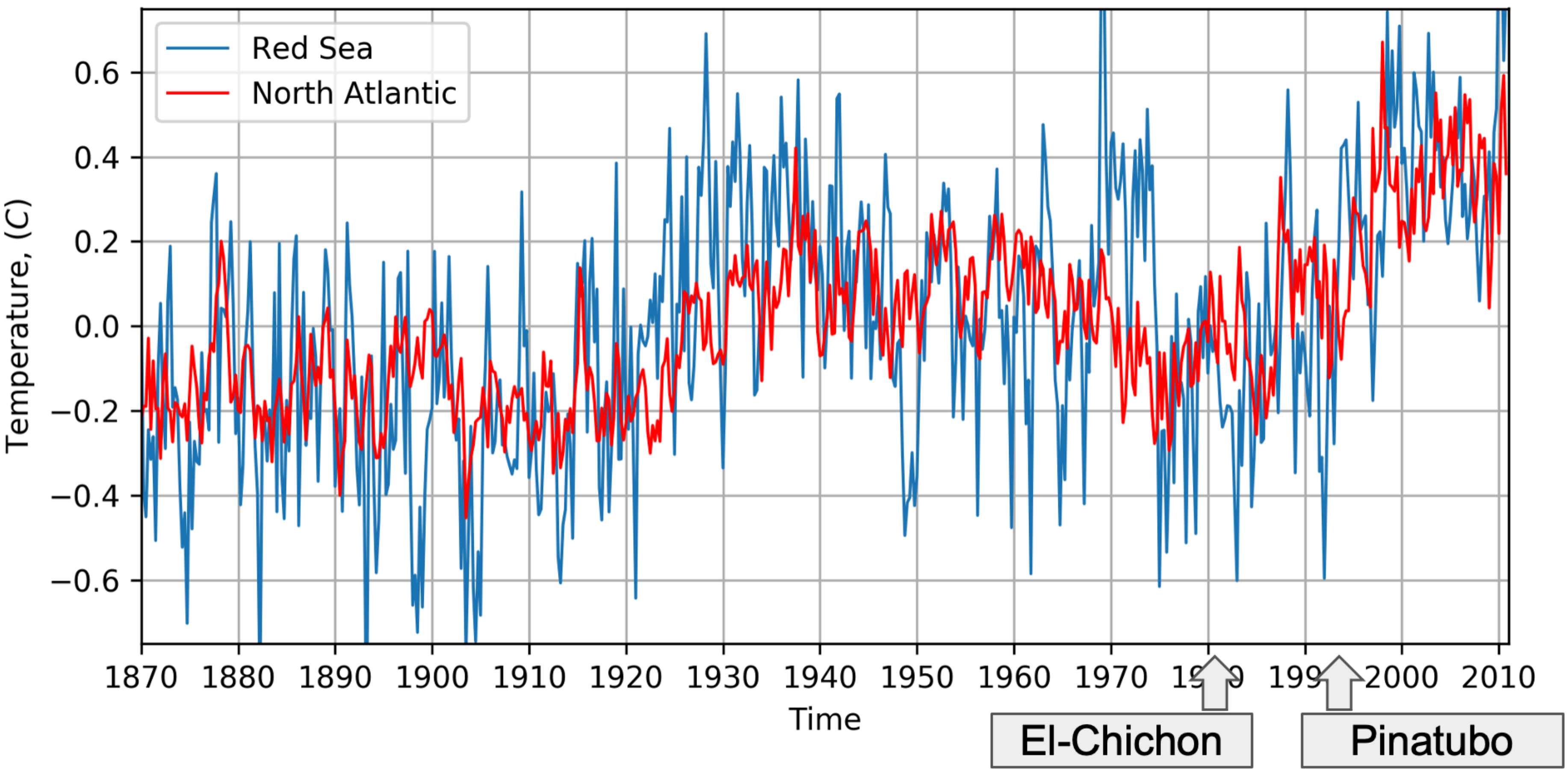
- For the first time, regional coupled modelling approach was successfully applied to study the severe post-Pinatubo winter cooling in the MENA region.
- Regional model captures well the dynamical response in the region (unlike global models).
- Observed cooling in the MENA region was dominated by the circulation changes forced by volcanic aerosol. Dynamical cooling is 2-3 times stronger than radiative.
- Strong post-Pinatubo Red Sea SST reduction up to -1 C was reproduced.
- Regional modeling approach provides a natural way to separate dynamical (through boundary conditions) and radiative (through prescribed aerosol optical properties) impacts and could be used along with the global modelling approach.

	Red Sea	Global ocean
SST anomaly peak	-1 C	3 times smaller
Main forcing	LH & SH	Solar dimming (SW)
Heat uptake time scales	0.5 years	15 year
Overturning anomaly	50%	10% (Atlantic Ocean)
Advection through the strait	Not perturbed	

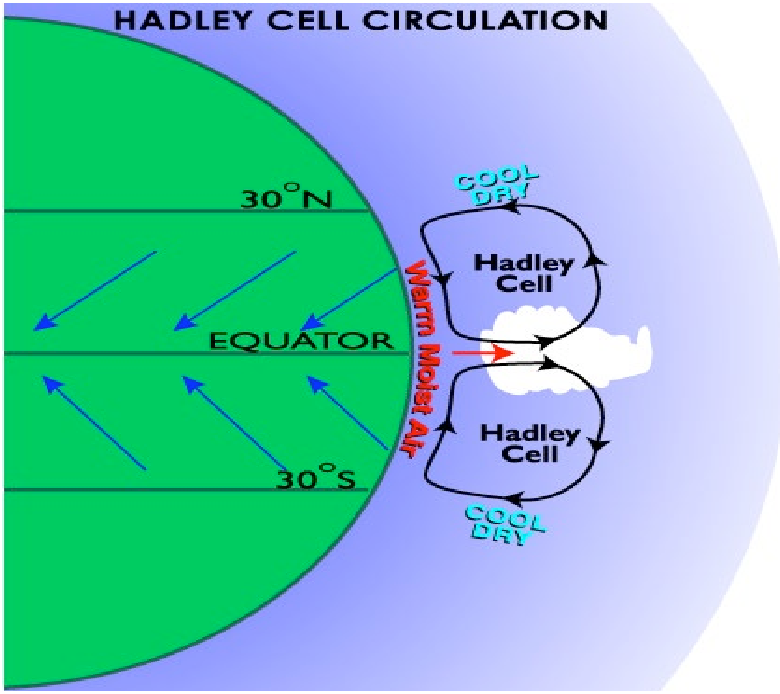
Dust Observations at the Red Sea coast

Natural variability in the Red Sea

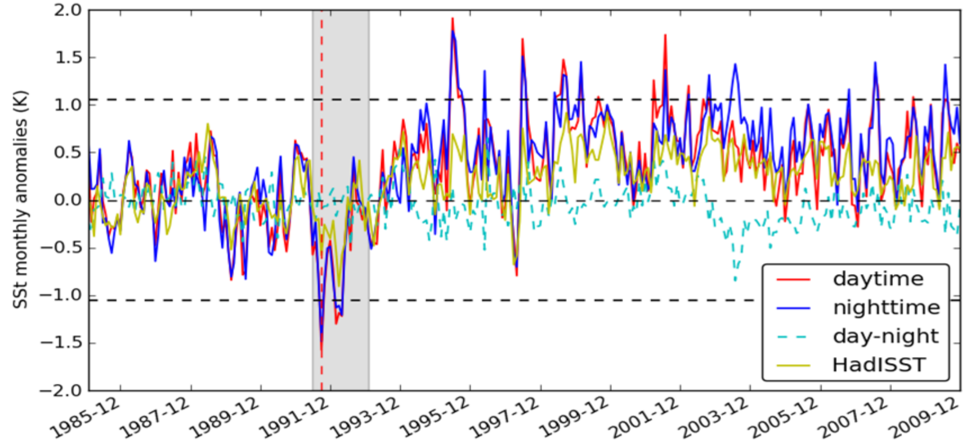
- Red Sea and North Atlantic SST variability exhibits a strikingly strong correlation
- Anomalies oscillate in a 60-70 year period
- The last warming cycle initiated in 1980 is rather abrupt, partly due to volcanic eruptions



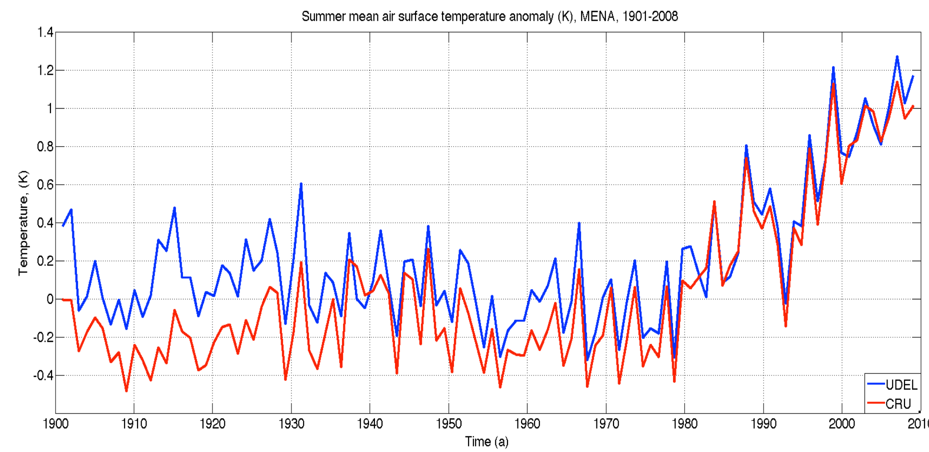
Area-weighted three-monthly Hadley SST anomaly since 1870 averaged over the Red Sea and North Atlantic (0N-70N, 100W-30E).



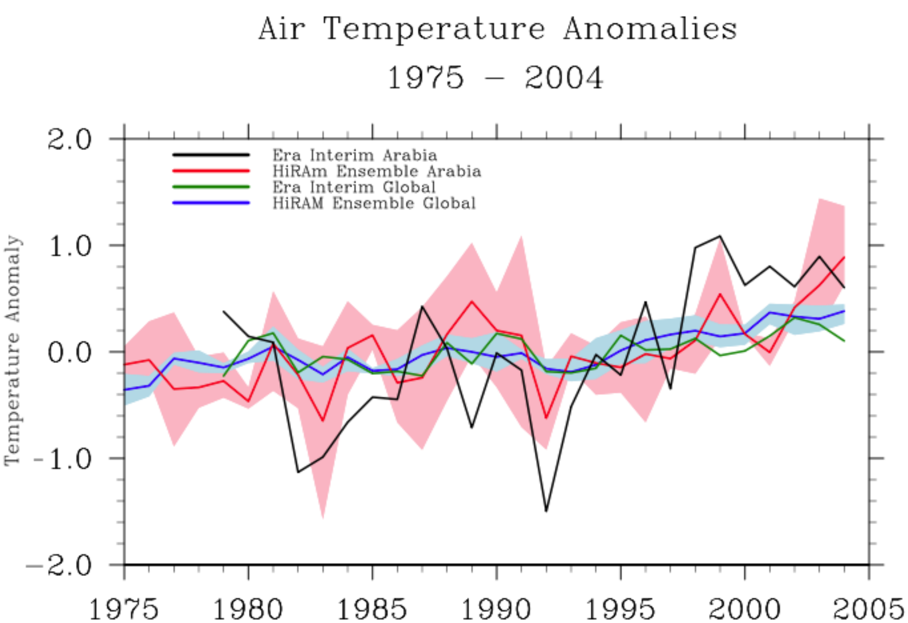
HADLEY CELL CIRCULATION
30°N
EQUATOR
30°S
Warm Moist Air
COOL DRY
Hadley Cell
Hadley Cell
COOL DRY



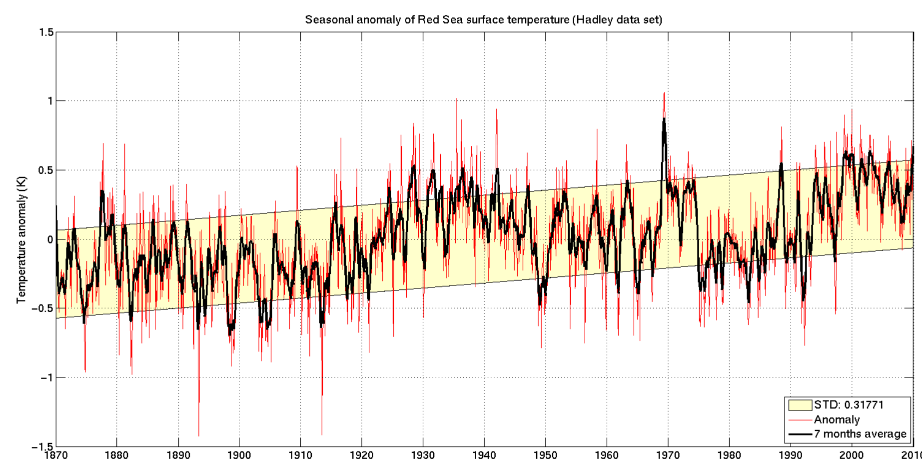
SSt monthly anomalies (K)
daytime
nighttime
day-night
HadISST
1985-12
1987-12
1989-12
1991-12
1993-12
1995-12
1997-12
1999-12
2001-12
2003-12
2005-12
2007-12
2009-12



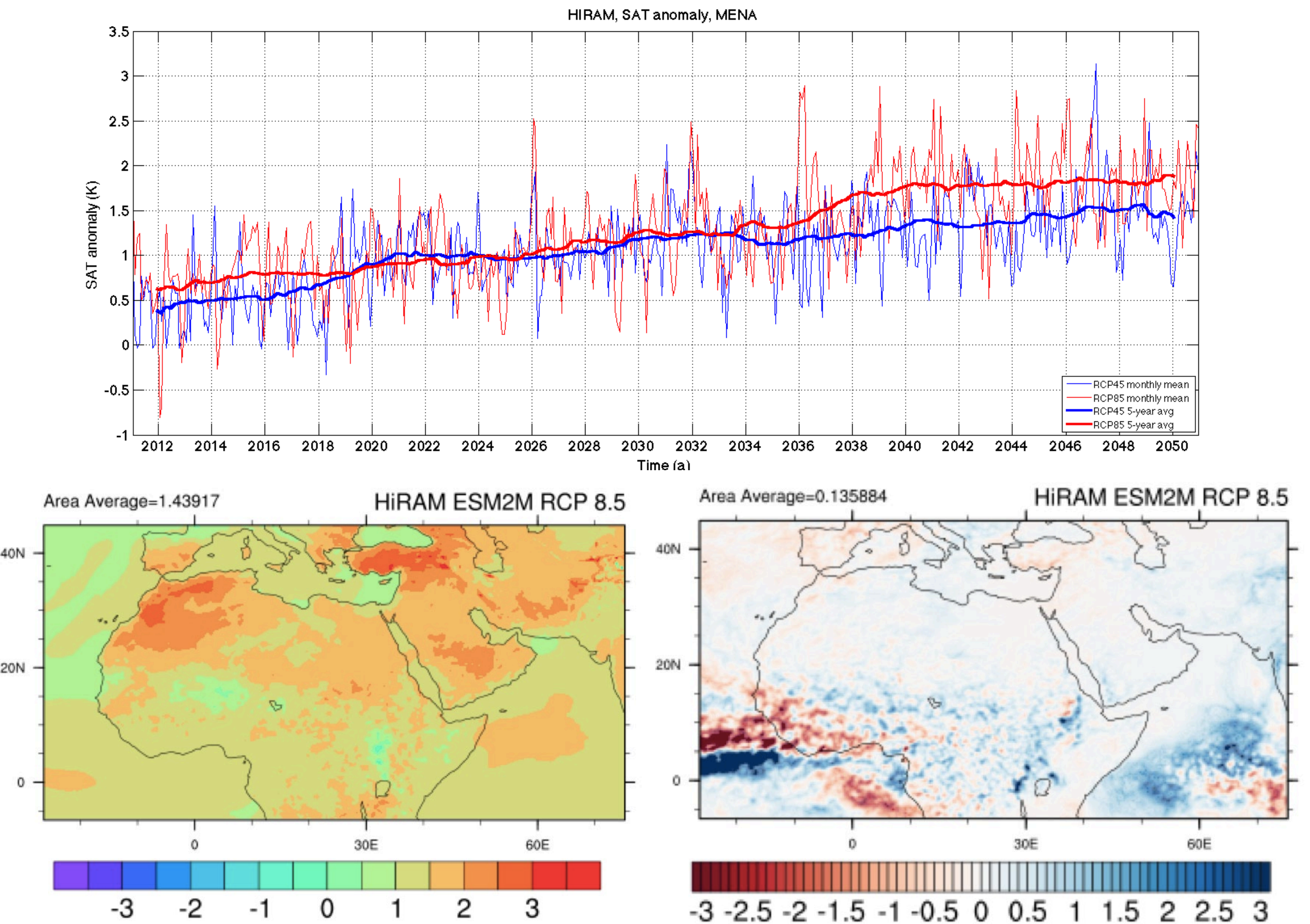
Summer mean air surface temperature anomaly (K), MENA, 1901-2008
Temperature, (K)
Time (a)
UDEL
CRU



Air Temperature Anomalies
1975 – 2004
Temperature Anomaly
Era Interim Arabia
HiRAm Ensemble Arabia
Era Interim Global
HiRAM Ensemble Global



Seasonal anomaly of Red Sea surface temperature (Hadley data set)
Temperature anomaly (K)
Time (years)
STD: 0.31771
Anomaly
7 months average

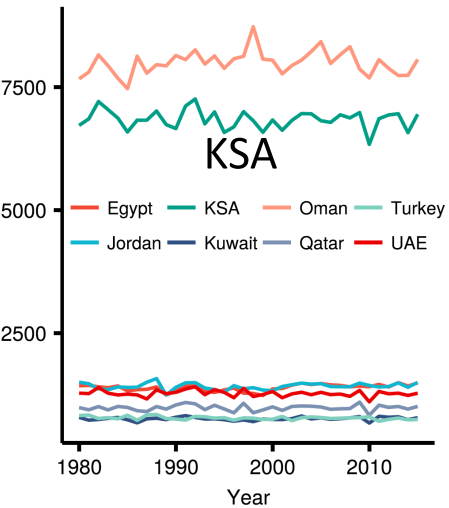


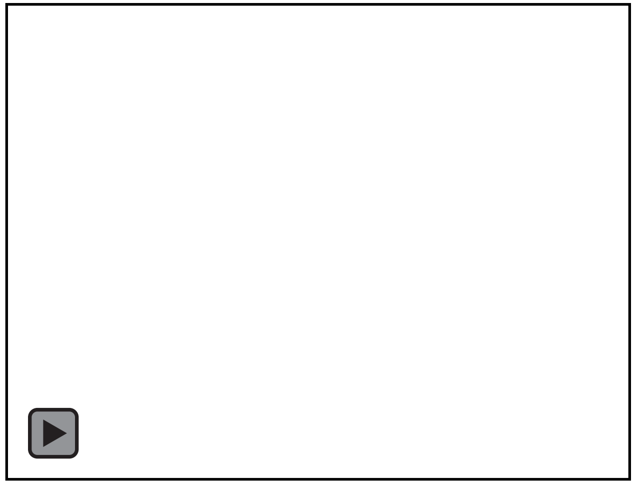
Surface Air Temperature (K)

Precipitation (mm/day)

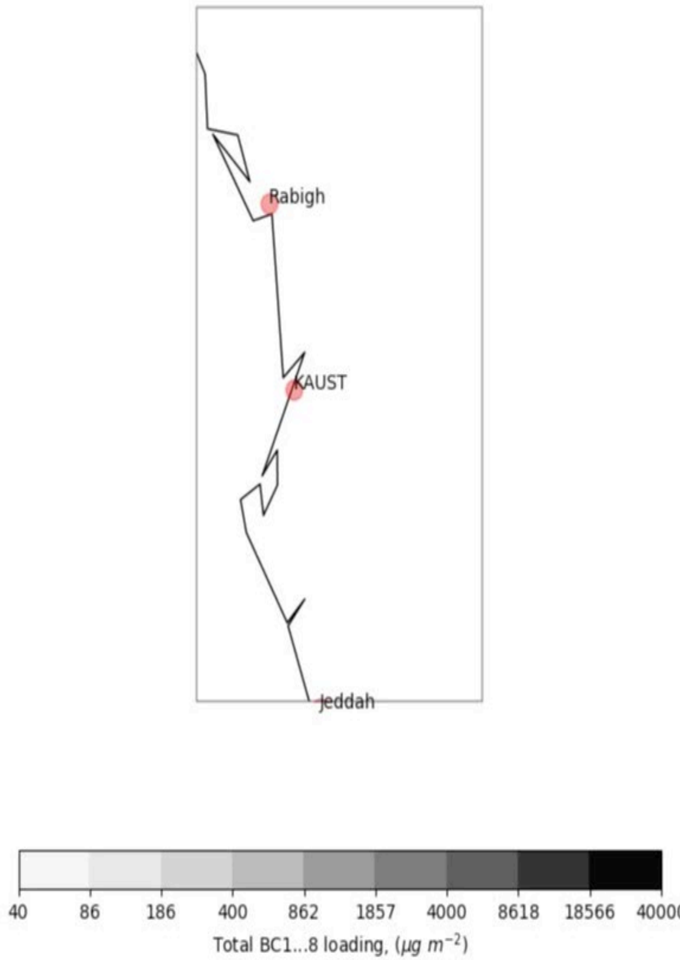
We use the same Modeling Technology to assess Airborne Wind Energy Resources and Conduct Hazard Management Studies

Airborne Wind Turbines Annual Generation (kWh) Per Capita

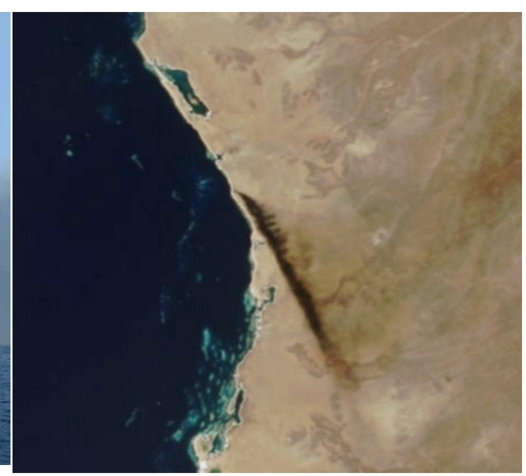




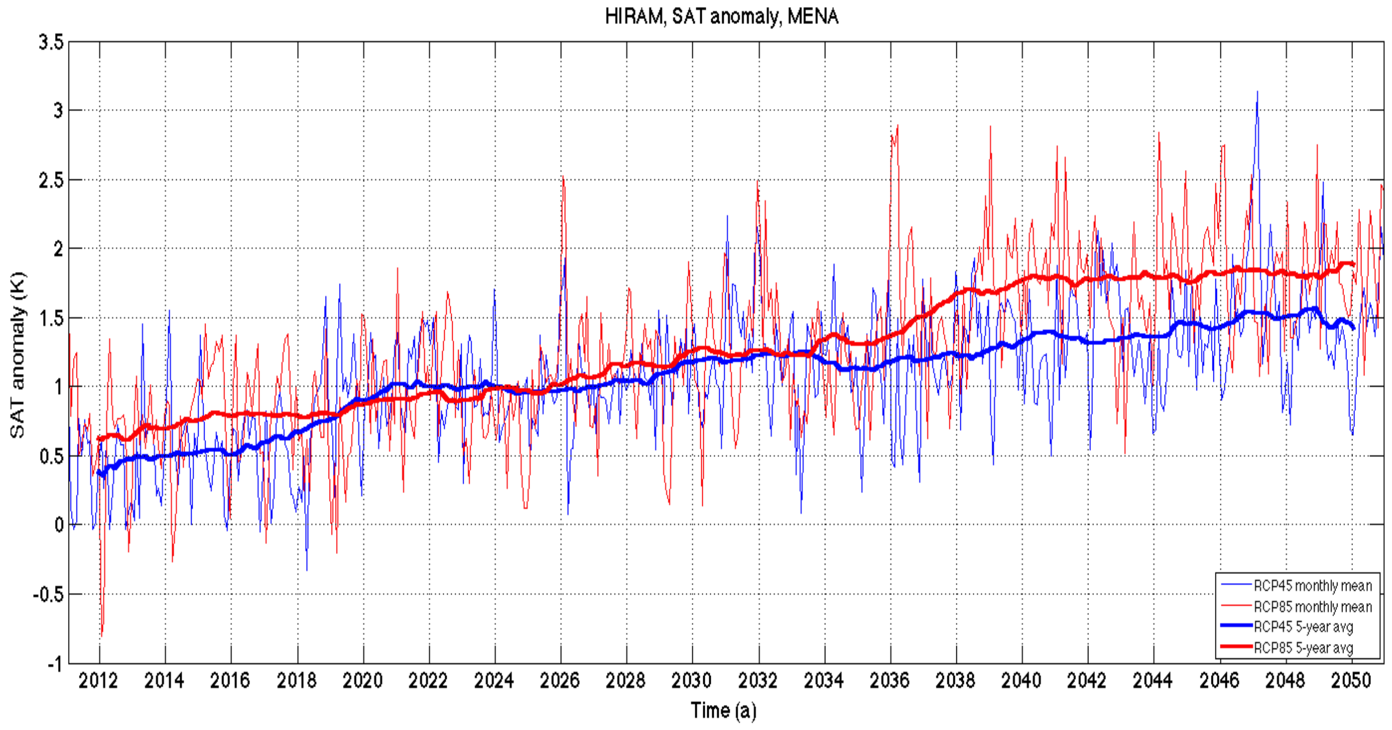
Simulation of Rabigh Fire



Oil Tanks Fire in Rabigh at Saudi Electric Company Power Plant on 9-11 April 2021

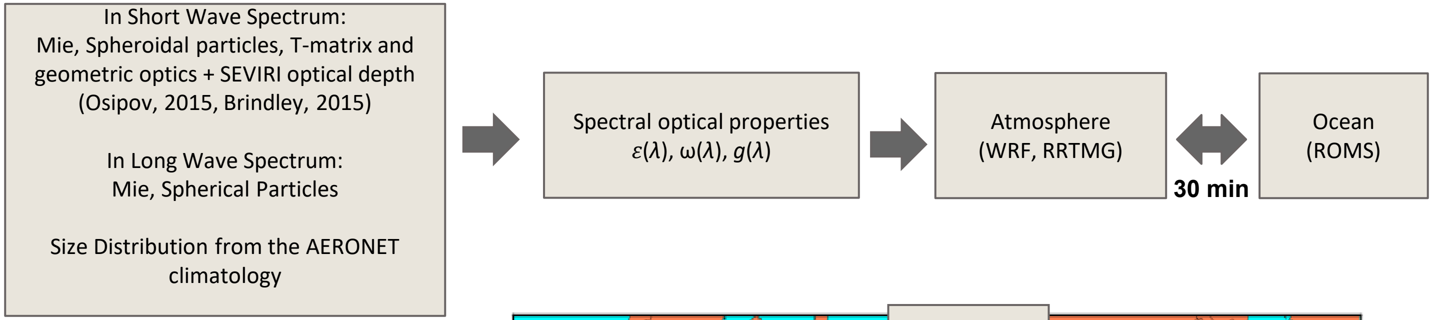


High-resolution Global Middle East and North Africa (MENA) Surface Air Temperature Projections with 25 km grid spacing



Mean Annual surface air temperature anomaly projection over the MENA region until 2050 in RCP4.5 and RCP8.5 emission scenarios. The projections are calculated at KAUST using global High-Resolution Atmospheric Model (HiRAM) with 25-km grid spacing.

Regional Dust Impact



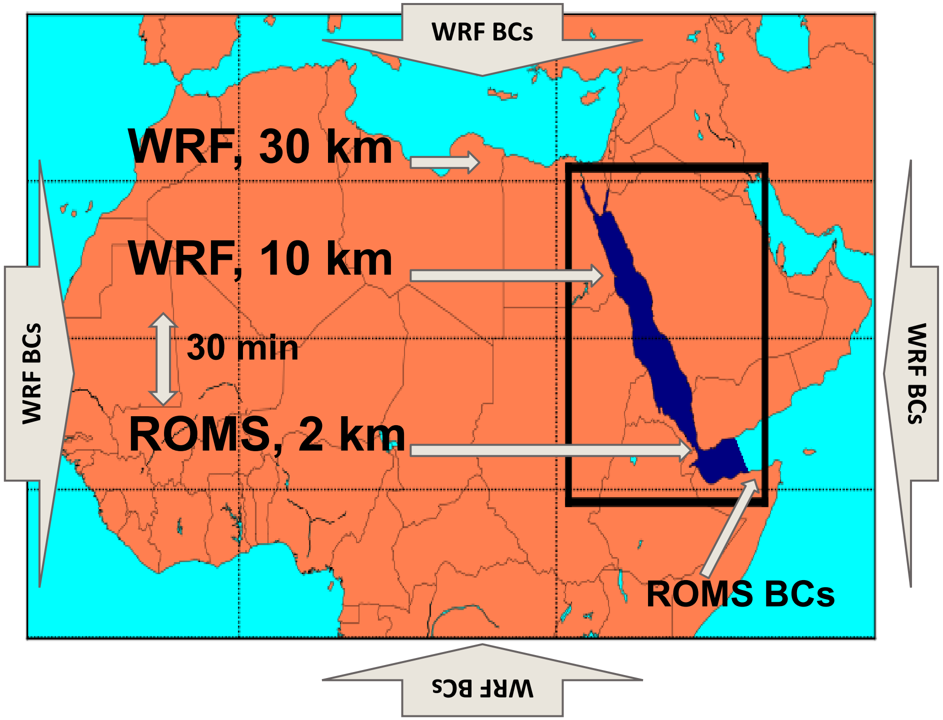
Framework:
A Coupled Ocean Atmosphere Wave Sediment Transport Modeling System (COAWST)

Atmosphere:
Weather Research and Forecasting Model (WRF)

Ocean:
Regional Ocean Modeling system (ROMS)

Boundary Conditions:
ERA-INTERIM

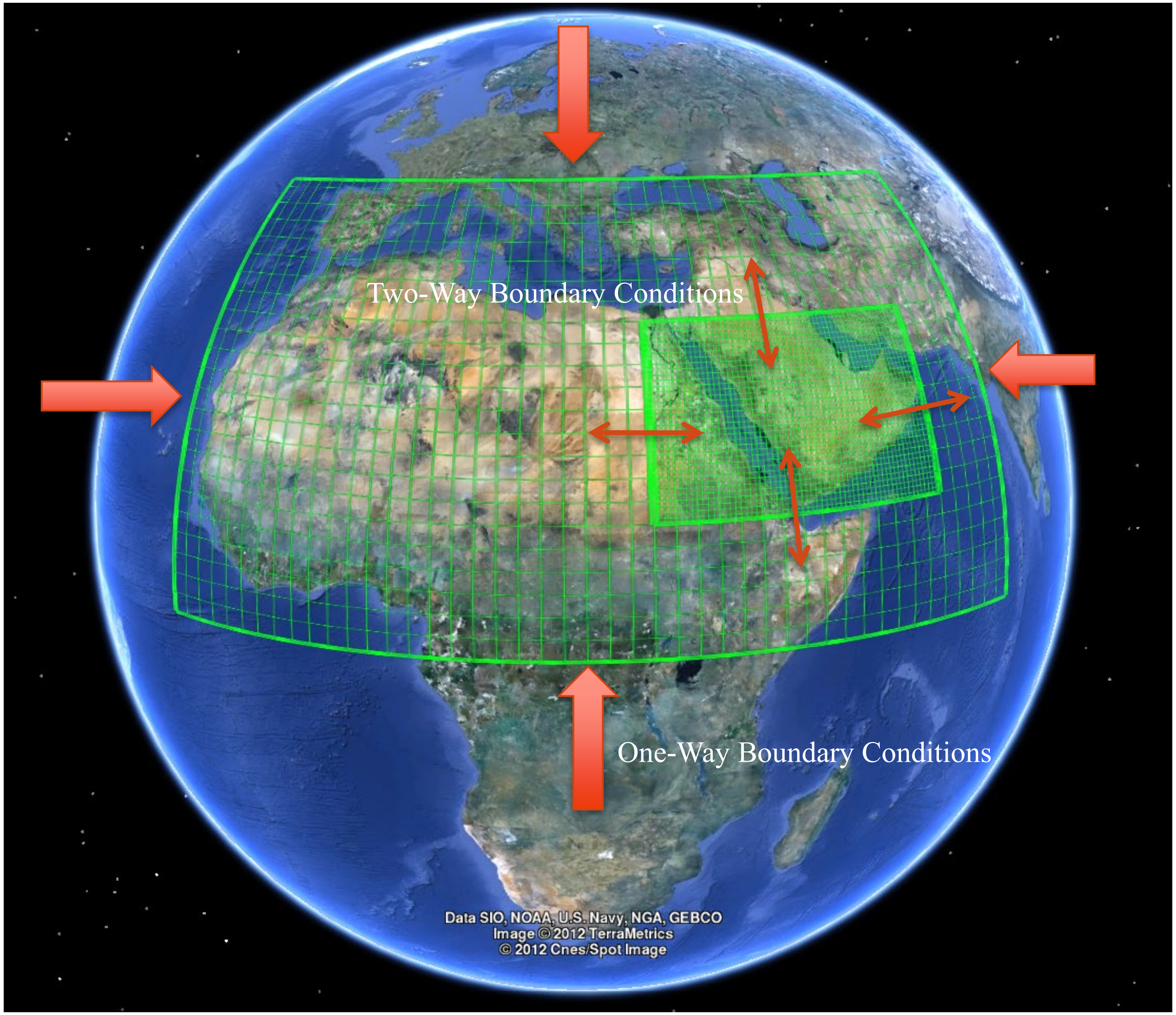
Experiments:
Perturbed (with DUST) – P
Control (without DUST) – C
Runs for the 1996-2016 period



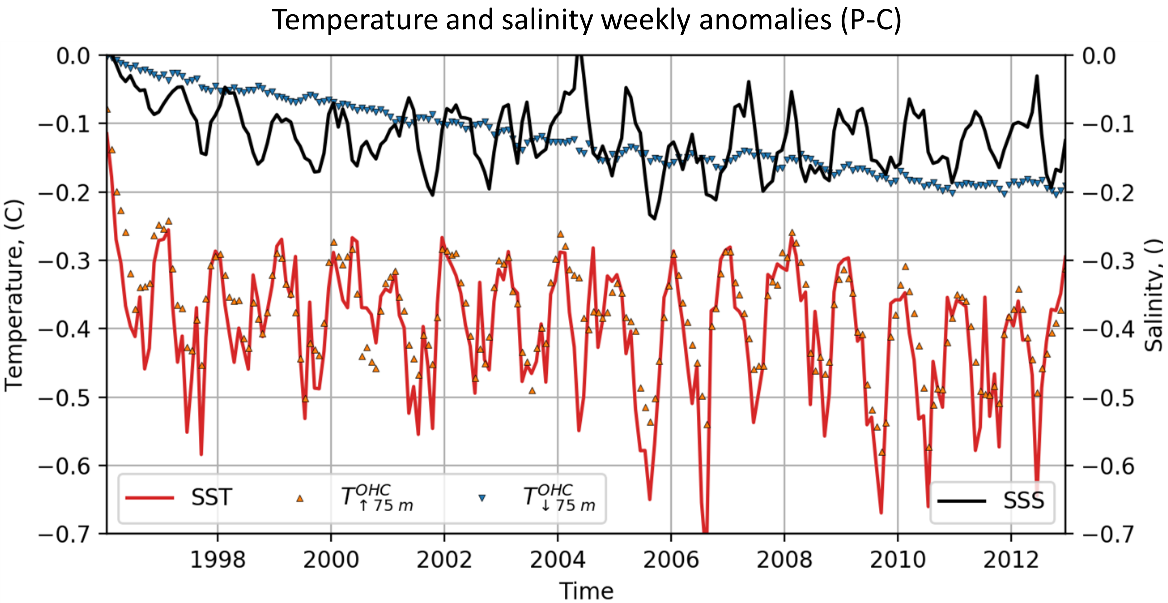
Regional Geoengineering to Increase Precipitation over the Red Sea Coastal Plain

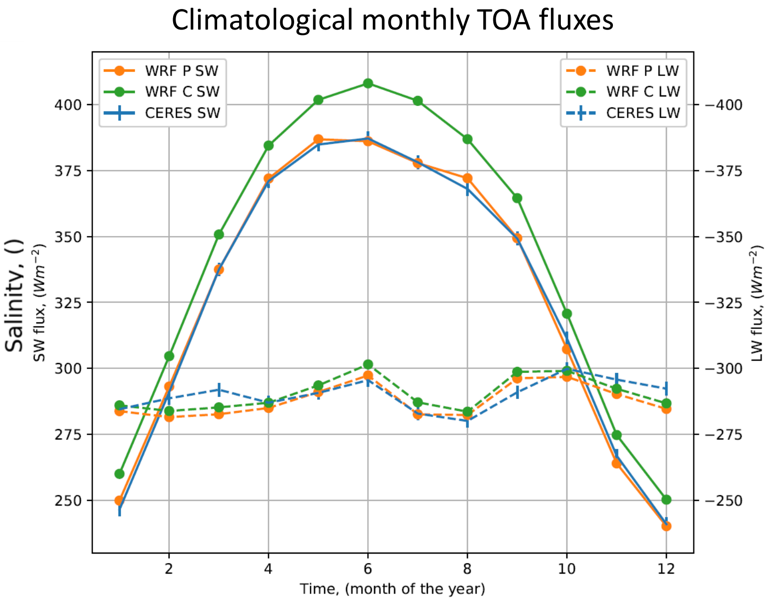
- Red Sea is the major natural resource and the major climatological entity
- Breezes circulate 1 Tt of water vapor from the Sea to the land
- Science question: Could precipitation be triggered by
    1. Coastal Afforestation – 1 billion trees (1/10 of Saudi Green Initiative)
    2. Surface albedo change or PV panel deployment in the coastal plain

Process Oriented Regional Model WRF-Chem



Thermal response and validation





	CERES TOA SW flux RMSE/Bias, (Wm^2)	CERES TOA LW flux RMSE/Bias, (Wm^2)	OISST-AVHRR SST RMSE/Bias, (C)
COAWST C	15.33/-14.65	4.55/0.37	0.78/-0.39
COAWST P	2.31/-0.30	4.79/-2.16	0.62/0.01

Root-mean-square error and bias comparison statistics for monthly climatological CERES TOA SW and LW fluxes and OISST-AVHRR SST in relation to COAWST P and C simulations. Statistics are computed in the observation-simulation sense.

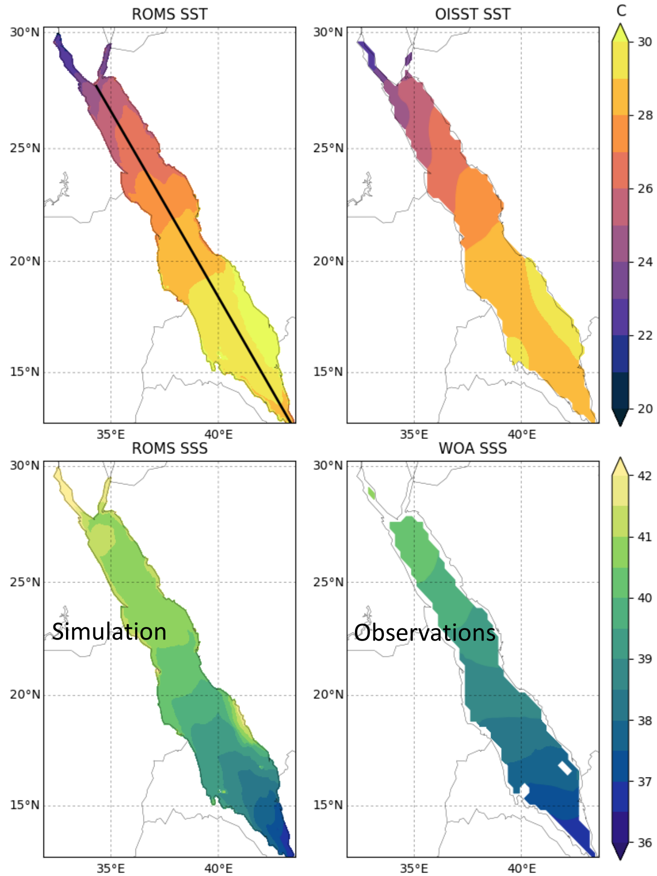
Ocean mean state

Red Sea is a concentration basin with inverse estuarine circulation at the strait of Bab el Mandeb.

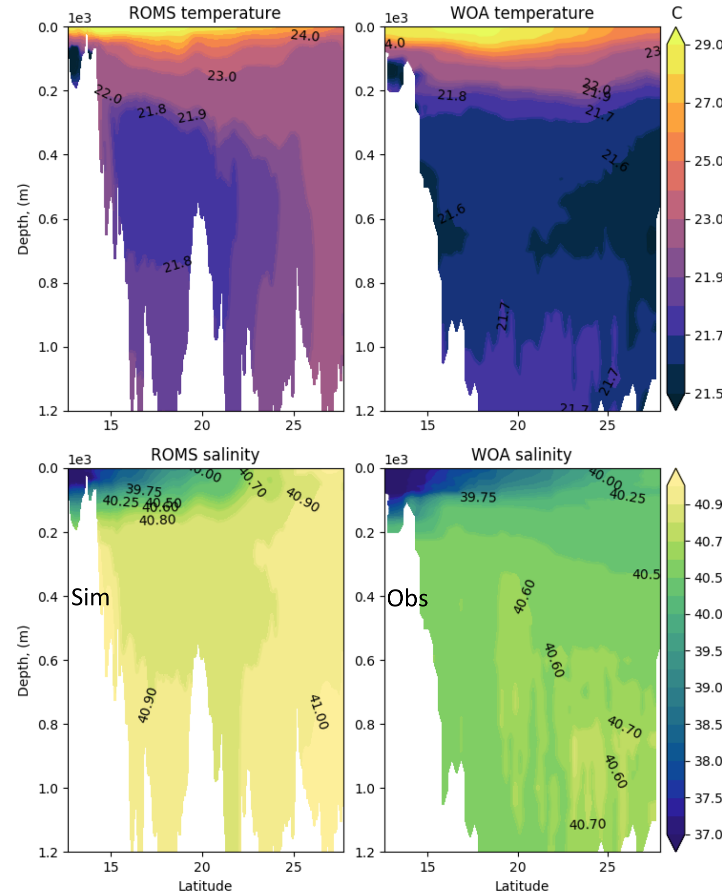
heat budget:
-3.75 Wm^{-2} (-11$\mp$5 Wm^{-2})

freshwater budget:
2.08 m year^{-1} (2.06$\mp$0.22 m year^{-1})

Surface T and S



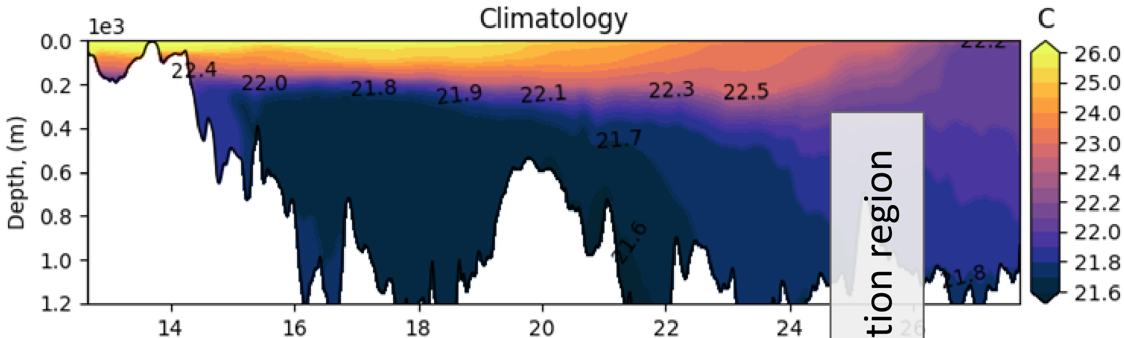
Vertical profiles of T and S



Volcanic Forcing Strengthens Red Sea Overturning by 50%

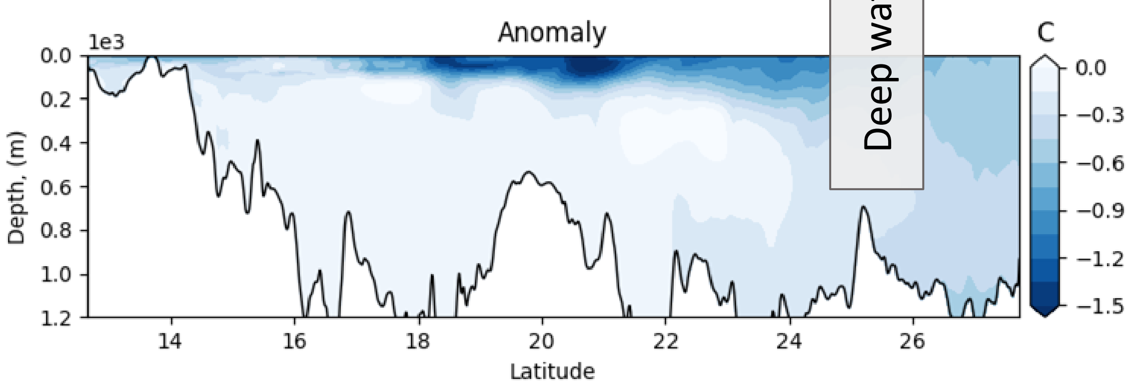
Weakly stratified water column and strong atmospheric cooling result in increased deep water formation and strengthening of the overturning circulation

Θ, winter (DJF) climatology

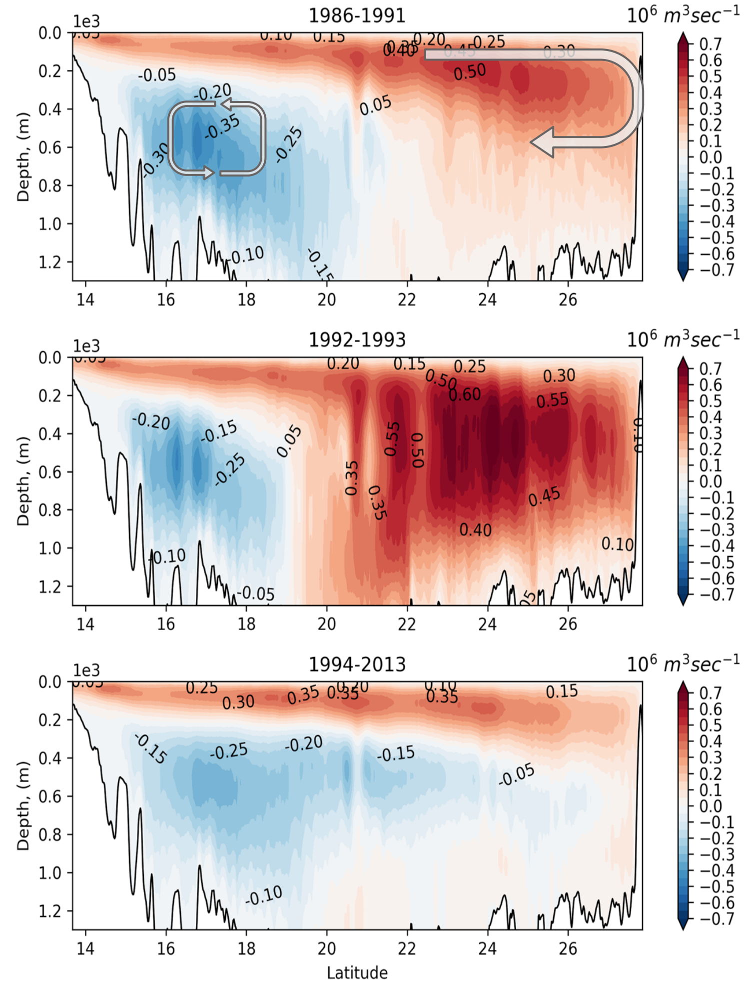


Deep water formation region

Θ, 1992 winter (DJF) anomaly wrt climatology

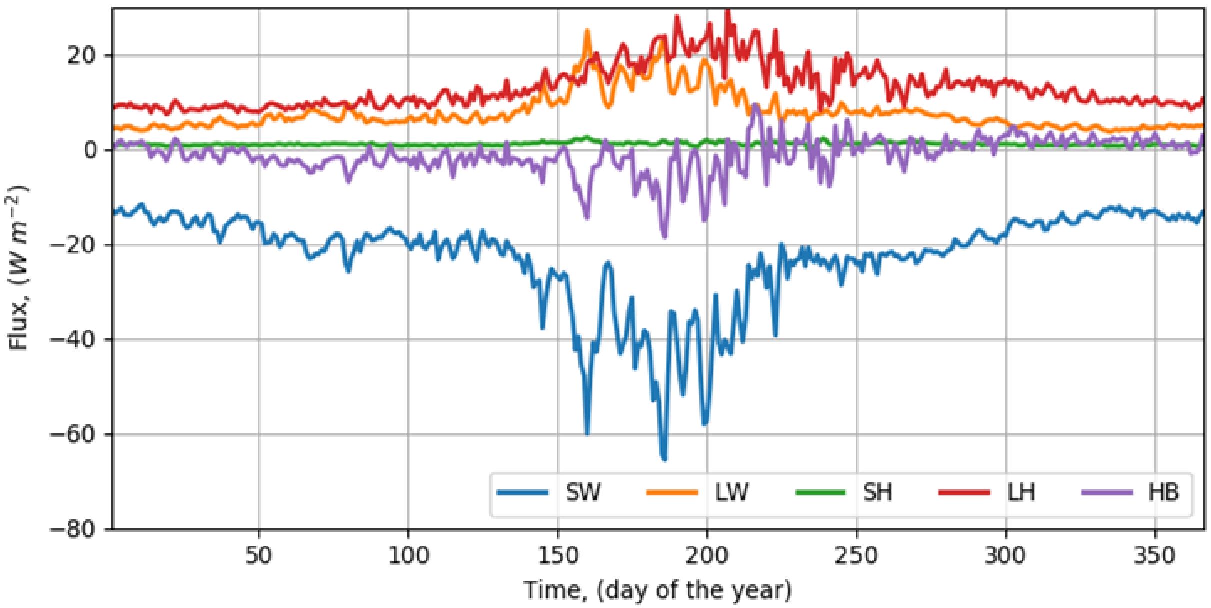


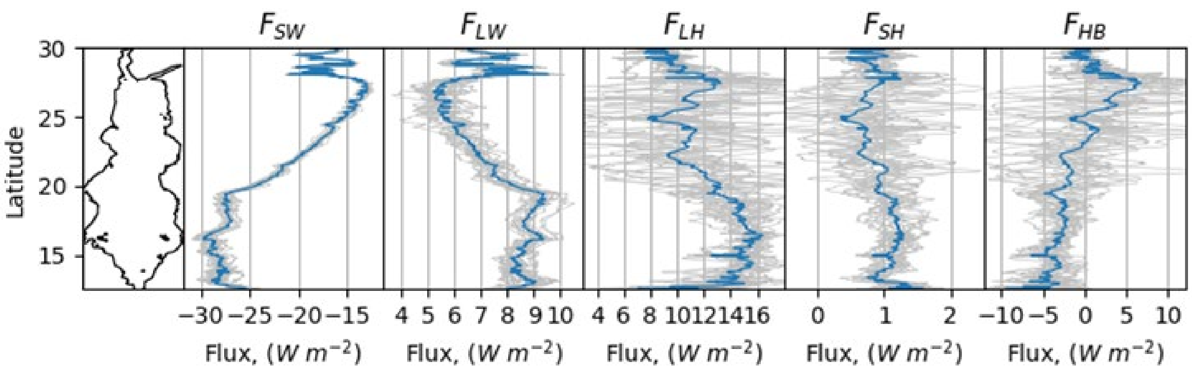
Overturning stream function response



Red Sea overturning time scales are 10 and 40 years for the 1st and 2nd cells, respectively

Dust radiative Impact on the Red Sea





- Heavy climatological dust loading over southern Red Sea during JJA
- Surface radiative SW cooling up to -60 Wm^{-2} and LW warming up to 20 Wm^{-2}
- SST response reaches -0.5 K
- Annual heat and freshwater budgets reduction by 3.2 Wm^{-2} and 0.086 m $year^{-1}$.
- Dust slows down the Red Sea overturning circulation by 5-10%