Regional Climate Modeling For the Asian-Australian Monsoon Region

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Outline

- Thermodynamics of MJO in a regional model with constrained moistening
- Development of South Asian Regional Reanalysis (SARR)
- Modeling effects of land use change and implications to droughts
- Modeling climate change and aerosol effects

Regional simulations of MJO

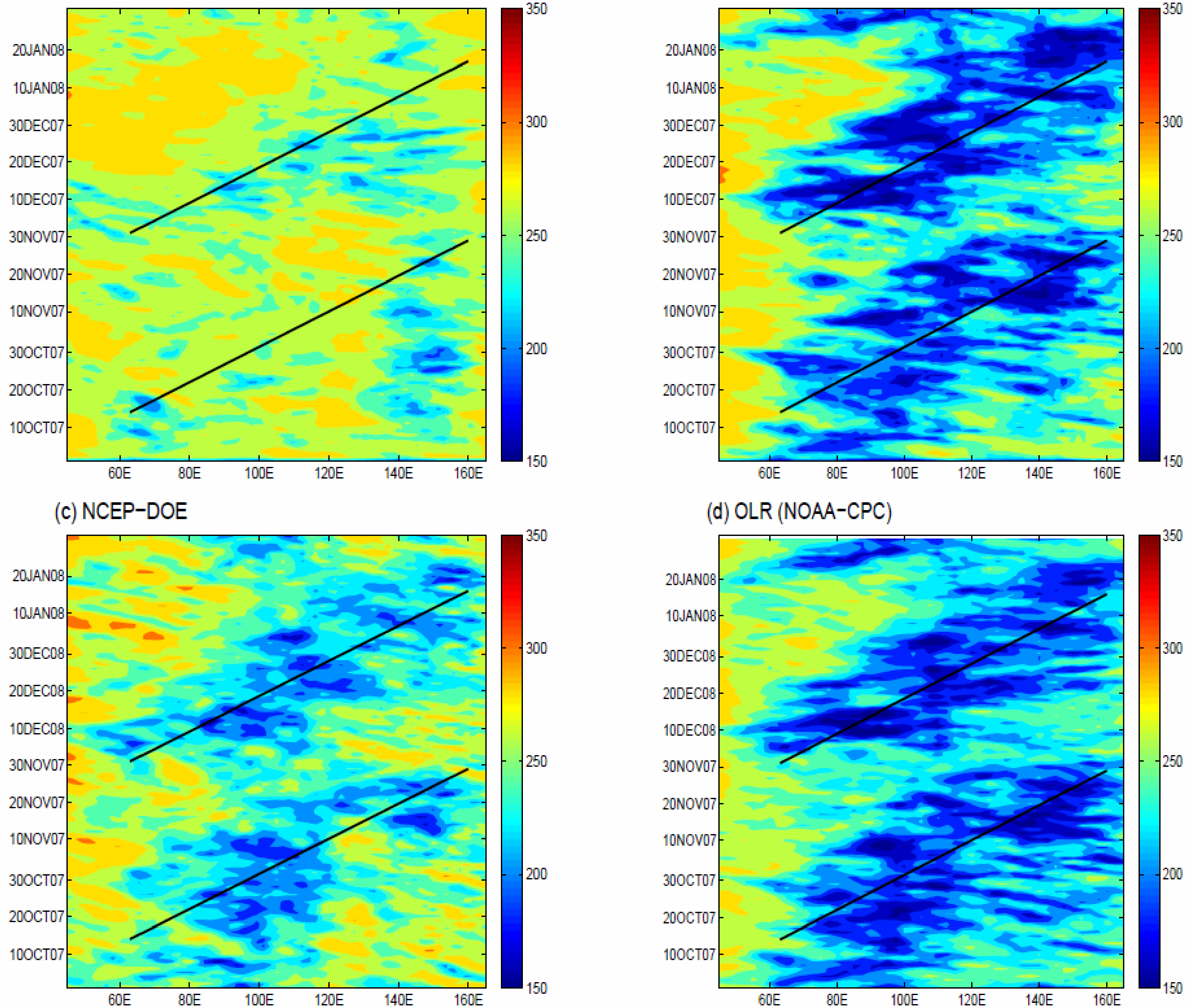
- Regional climate simulations using the Weather Research and Forecasting (WRF) model have been performed with constrained moistening:
  - Thermodynamic budget analysis is used to identify the main sources and sinks of energy associated with MJO convective activity, and the roles of various types of instabilities in the propagation and lifecycle of MJO are evaluated
  - By systematically evaluating the effect of the moistening constraint on the model simulation, an insight is gained into the physical processes that are critical for robust, realistic simulation of MJO

Model configurations

- WRF is applied at 36km resolution over a domain that includes Indian Ocean and Western Pacific and covers 25S to 25N
- GFS forecast data are used to provide lateral, initial, and surface boundary conditions
- The Kain-Fritsch, RRTM, YSU and WSM-3 schemes are used to parameterize cumulus convection, radiation, PBL and microphysics respectively
- In the GFDDA experiment the simulated moisture is nudged toward the GFS analysis every six hours with a relaxation timescale of 15 minutes
- The NONUDGE experiment has no nudging in the interior of the domain
- Two MJO episodes observed during the winter of 2007-2008 were simulated

Comparison of simulated and observed OLR signals

Simulation w/o nudging | **Simulation with moisture nudging**

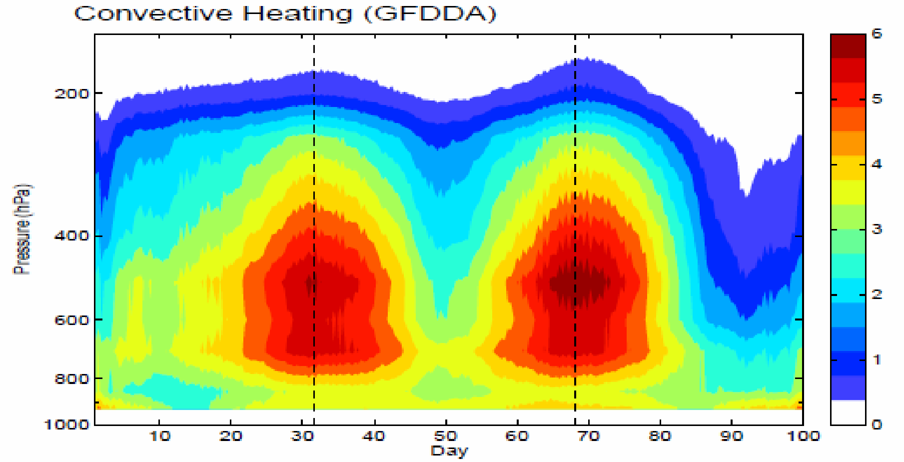


NCEP-DOE reanalysis | **NOAA-CPC observation**

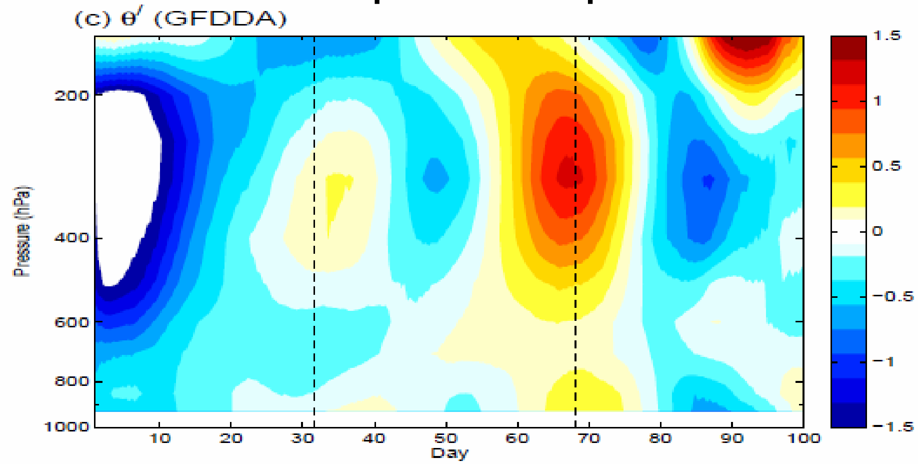
Composites from the GFDDA simulation

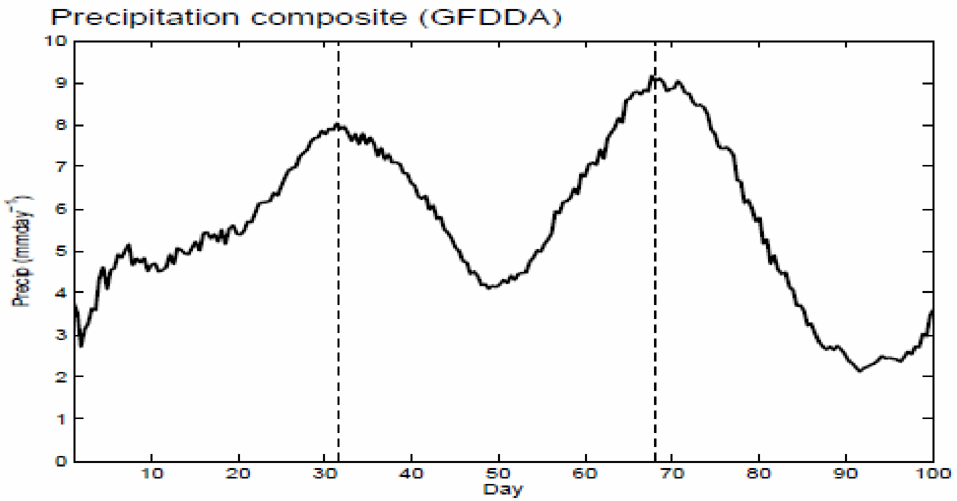
- Composites are developed using a frame of reference that follows the MJO that propagates at about 4 m/s
- Two MJO episodes are identified with peak precipitation at day 32 and 68 of the 120 day simulation

Convective latent heating



Potential temperature perturbations





Precipitation

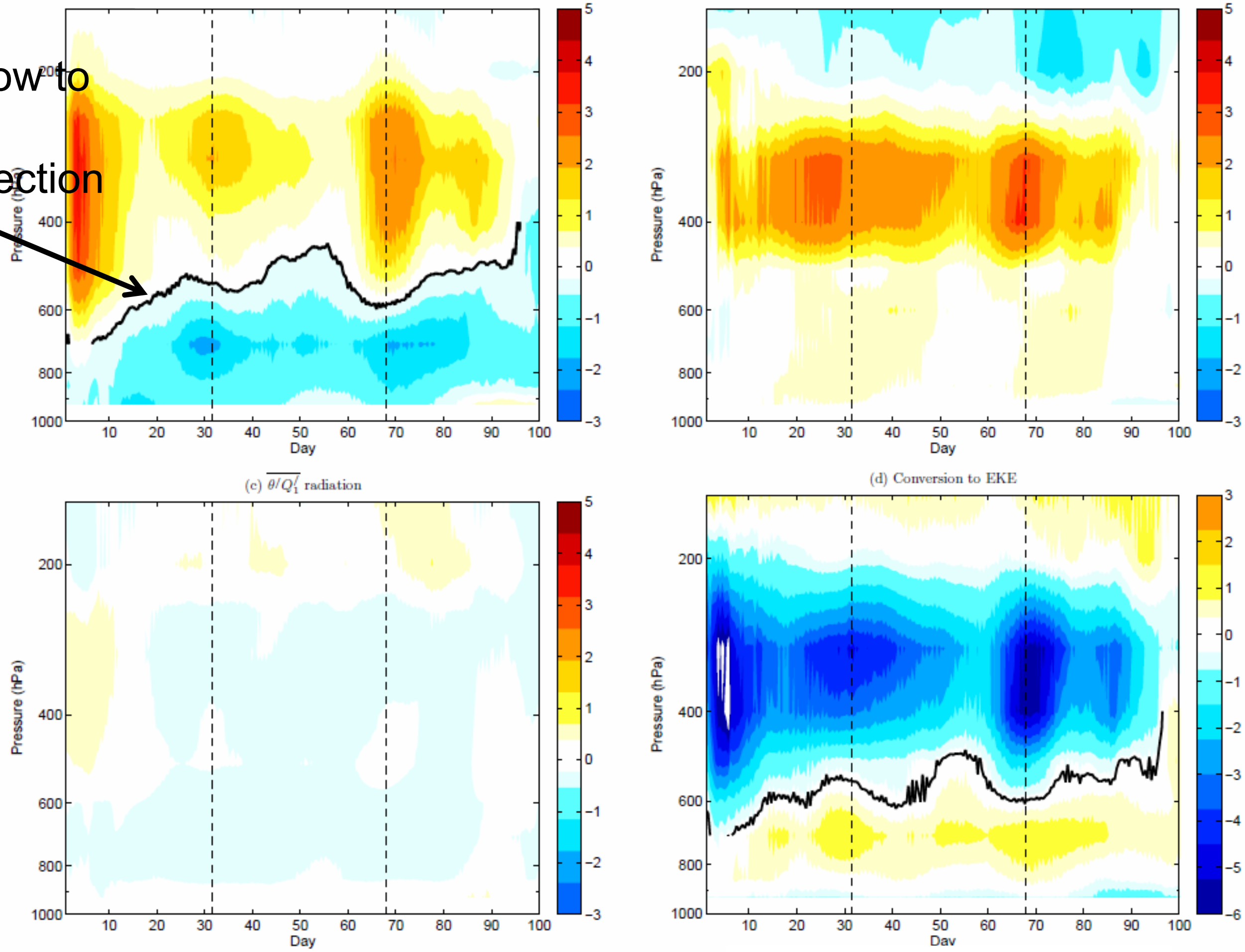
Sources and sinks of available eddy potential energy

$$\frac{\partial \overline{\theta'\theta'}}{2\partial t} = -\overline{\theta'(\nabla\cdot(\mathbf{v}\theta))'} + \overline{\theta' Q'_{1(conv)}} + \overline{\theta' Q'_{1(stratiform)}} + \overline{\theta' Q'_{1(radiation)}} + \overline{\theta' Q'_{1(pbl)}}$$

Transition from shallow to deep convection

$\overline{\theta' Q'}$ Convective

$\overline{\theta' Q'}$ Stratiform



$\theta' Q'$ Radiation

Conversion to EKE

- In the lower troposphere EKE conversion and stratiform instability are sources of EAPE and shallow convective heating is a sink (convective damping layer)
- In the upper troposphere stratiform instability and convective heating (wave-CISK) are the main sources of EAPE and conversion to EKE is the sink

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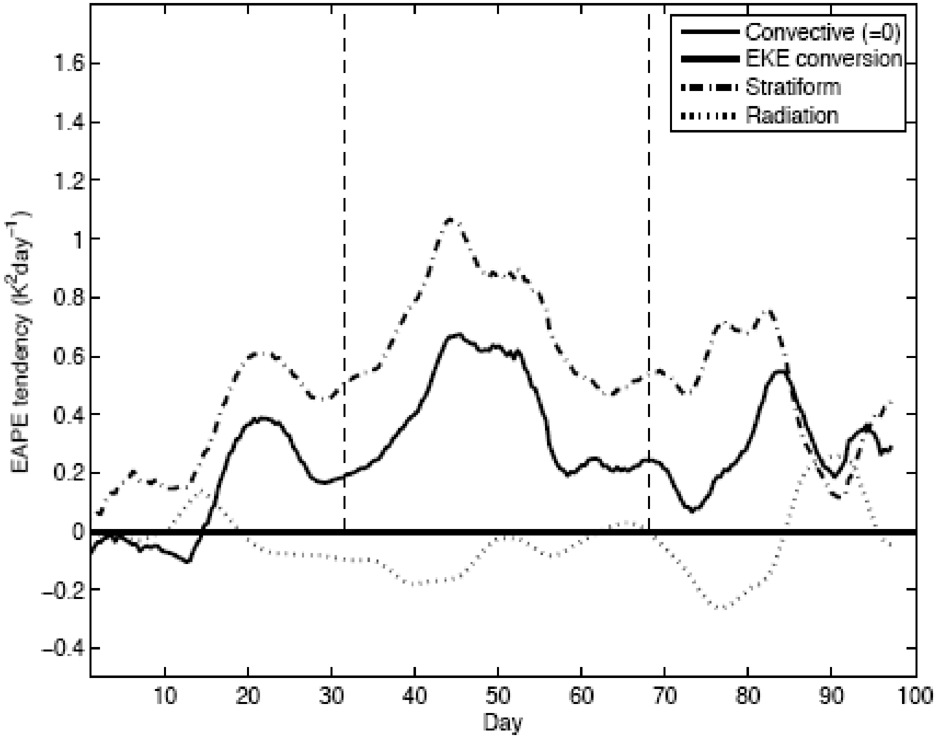
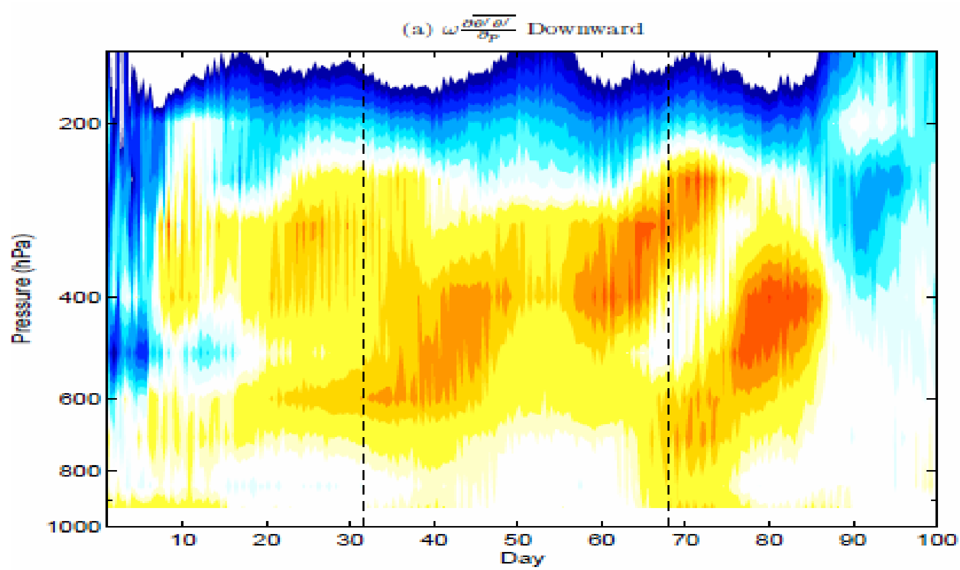
What triggers the transition from shallow to deep convection

- EKE is mainly provided by stratiform heating as the transition level progresses up and taps the energy from stratiform instability
- The subsidence of cold air provides the EAPE for gradual deepening of the convective damping layer toward the layer of stratiform instability upon which deep convection is triggered



EAPE budgets at the transition level



Downward transport of EAPE

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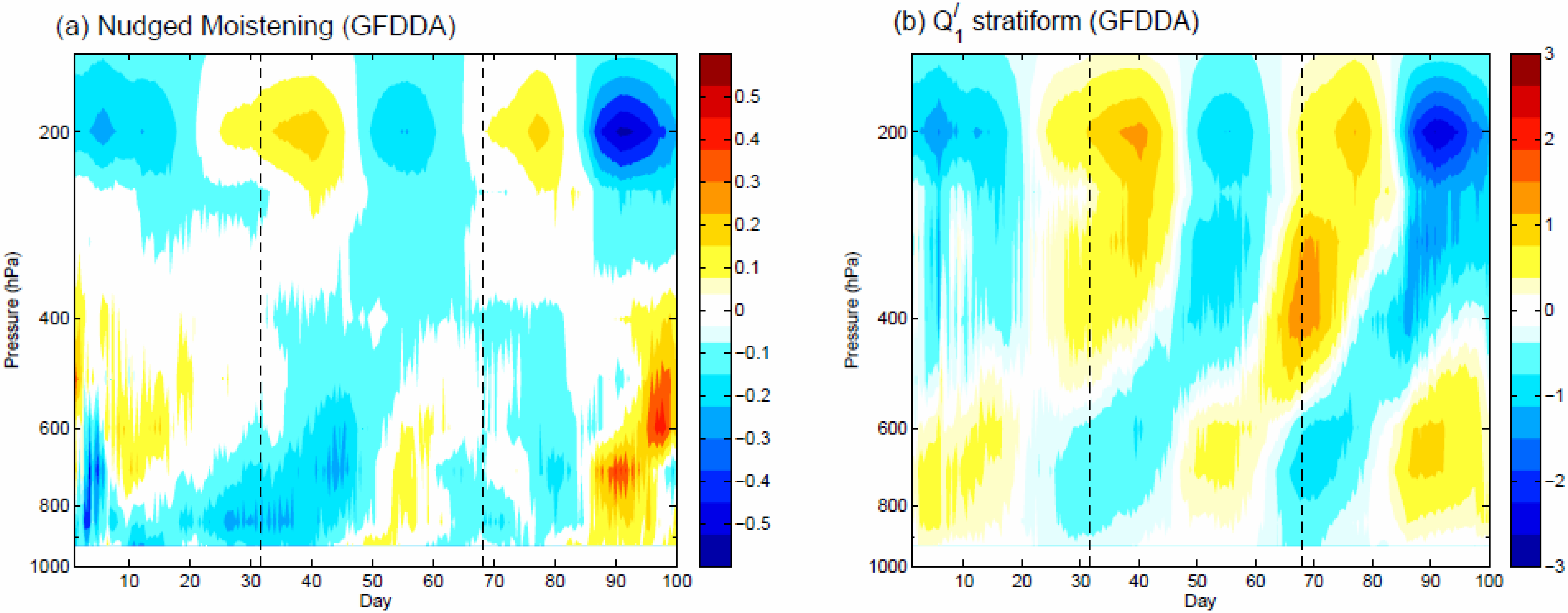
Perturbations by observational nudging

- Nudging moistens the lower troposphere about 15 days before the MJO peak precipitation and it moistens the upper troposphere for up to 15 days after the precipitation maxima
- The stratiform heating associated with low-level (and upper level) moistening during early (and late) stages of the MJO active phase results in EAPE generation throughout the troposphere
- The tilt in stratiform heating variability is needed for positive co-variability with potential temperature perturbation to generate constant stratiform instability

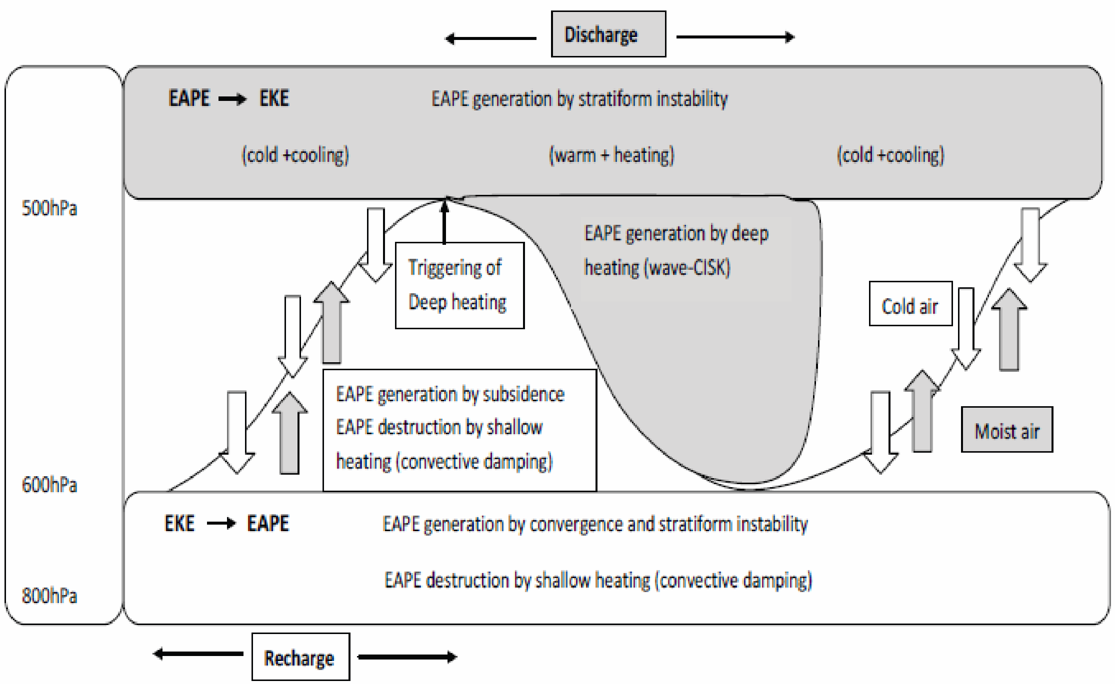


Perturbation of moistening

Perturbation stratiform heating

A simplified paradigm of MJO thermodynamics

- In the ‘stratiform instability layer’ between 500hPa and 300hPa, EAPE is constantly generated by covariance between stratiform heating and potential temperature
- In the lower troposphere, EAPE is converted to EKE in the ‘convective damping layer’ and stratiform instability is damped by shallow convective heating that also moistens the layer
- The convective damping layer is gradually deepening due to EAPE generation by subsidence. As it rises and reaches the stratiform instability layer, this mechanism of EAPE generation becomes available and allows the air parcels and moisture to rise deep into the upper troposphere triggering deep convection
- Once deep convection is triggered the wave-CISK mechanism of generating EAPE takes over and the damping layer rapidly shrinks back to the lower troposphere where the subsidence once again starts to deepen it for the next MJO cycle

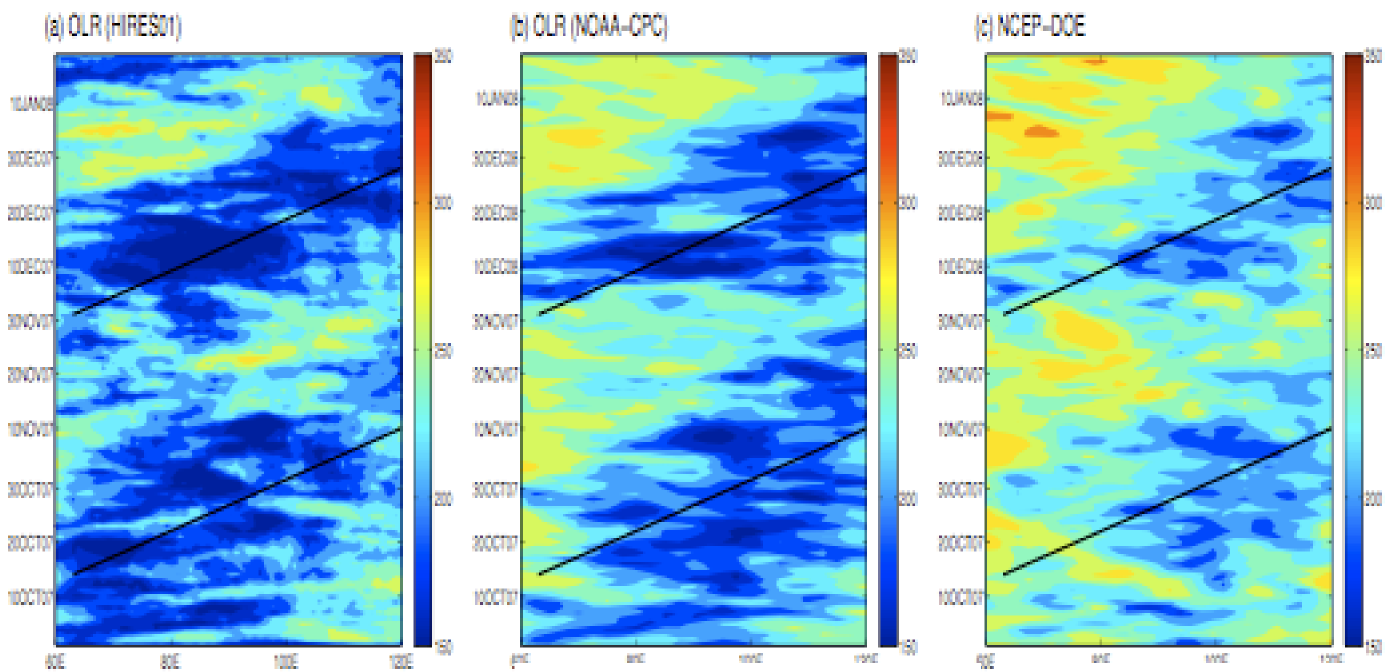


Summary

- The thermodynamics of MJO has been studied using regional simulations with constrained moistening
- Lower (upper) level moistening at the early (late) stages of the MJO active phase is found to be crucial for the life cycle of the MJO - it introduces the tilt in stratiform heating variability that interacts with potential temperature perturbations and provide an important source of EAPE
- Without moisture nudging, the regional simulation was not able to produce the necessary tilt in stratiform heating
- More sensitivity experiments using different combinations of deep and shallow convective parameterizations show some successes in simulating features of MJO, although the propagating signals for precipitation are still weak
- Cloud resolving simulations will be performed to further provide insights on both the thermodynamic and moisture budgets of MJO to guide parameterization development

Summary

- Regional models are useful for MJO study:
  - Different types of numerical experiments can be readily performed with grid or spectral nudging to produce realistic simulations for budget analysis
  - By imposing lateral boundary conditions, extratropical influence can be evaluated
  - It is feasible to perform cloud resolving simulations with the regional model dynamical core to explicitly resolve deep convection for a full energy and moisture budget analysis



WRF simulation at 4 km resolution **NOAA-CPC observation** **NCEP-DOE reanalysis**

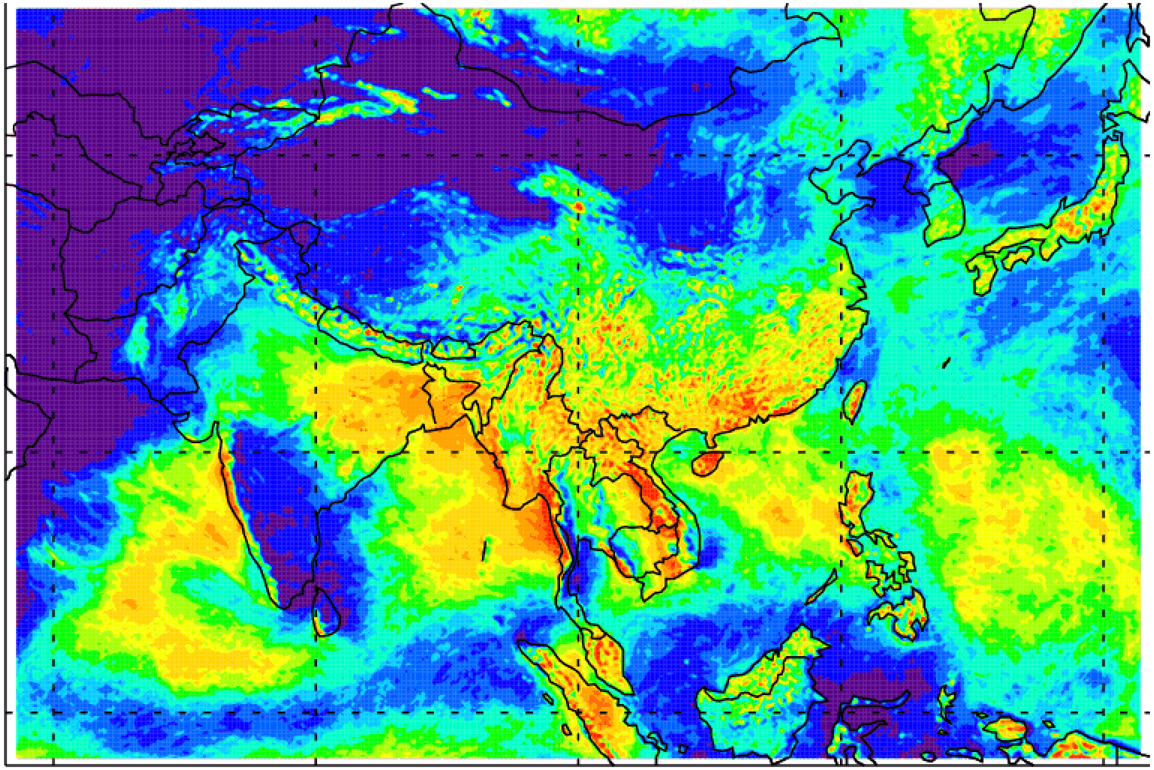
Development of South Asian Regional Reanalysis (SARR)

- An MOU has been signed between Ministry of Earth Sciences (MoES) of India and NOAA to develop SARR to advance Understanding, Modeling, and Prediction of Monsoon Hydroclimate Variability and Change
- SARR will be a retrospective analysis (reanalysis) of circulation and thermodynamic fields over South Asia
- Interest in regional hydroclimate (precipitation, surface temperature, soil moisture, streamflow, drought indices, etc) is intense and growing, given the direct societal impacts
- Through additional assimilation of precipitation, radiance, and aerosol observations in numerical weather prediction models, SARR will generate refined description of the regional hydroclimate state

Example: A poor man's regional analysis based on WRF

- WRF is applied at 18 km resolution driven by GFS large scale conditions for 1997-2008
- The large scale circulation in WRF is constrained by GFS using spectral nudging

Simulated JJA precipitation for 1997



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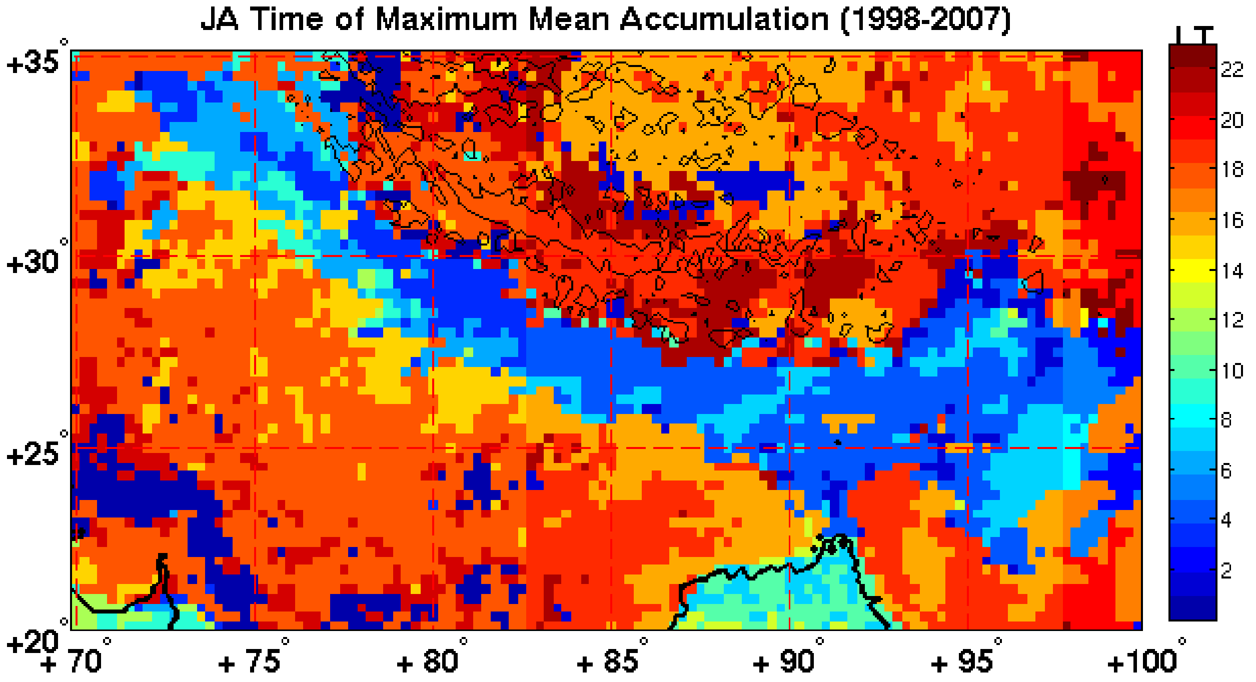
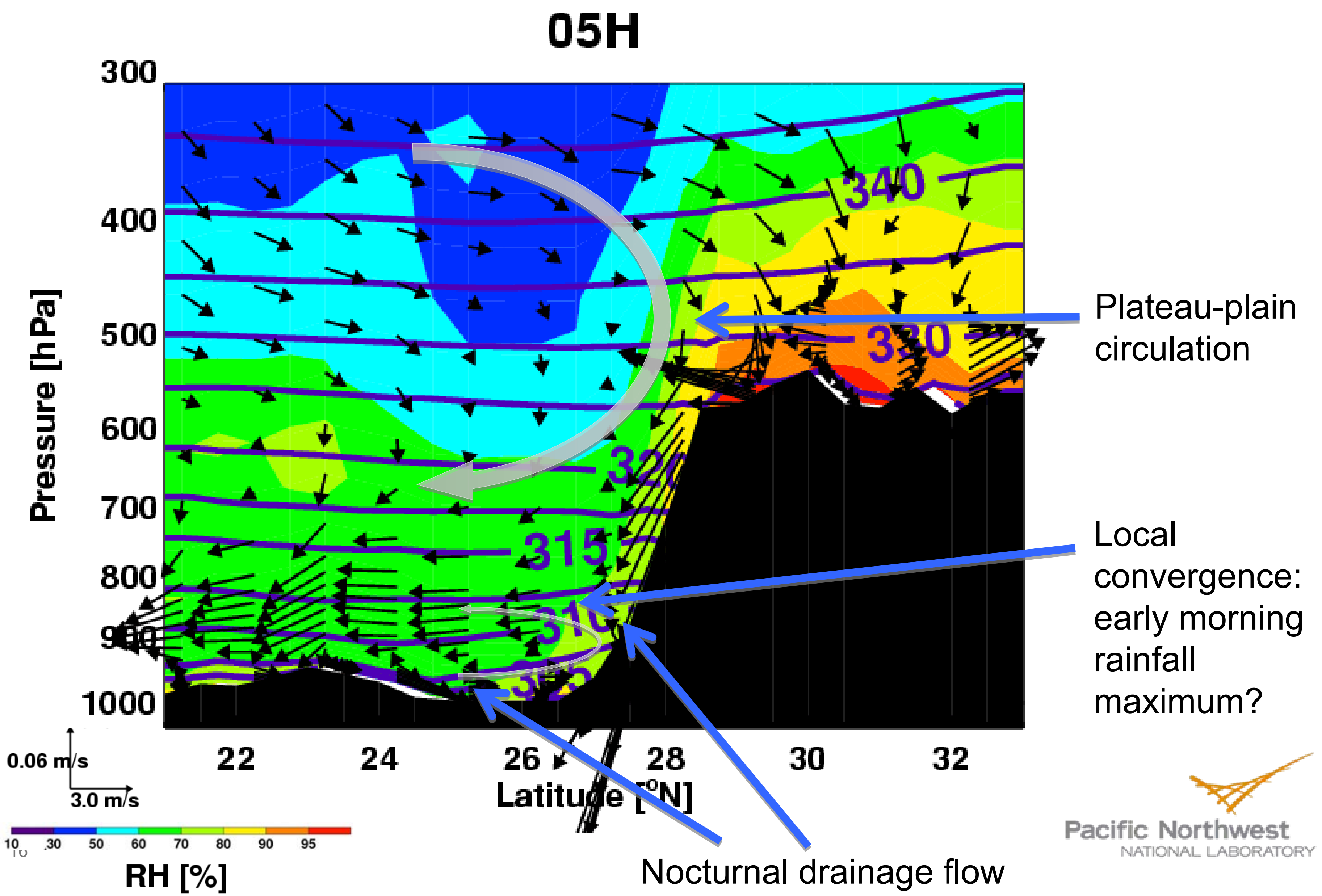
Terrain effects near the Tibetan Plateau

- Note the distinct early morning rainfall timing at the foothills of the plateau and late afternoon/early evening timing on top of the plateau



Dynamical and thermodynamical processes in the boundary layer near the Tibetan Plateau



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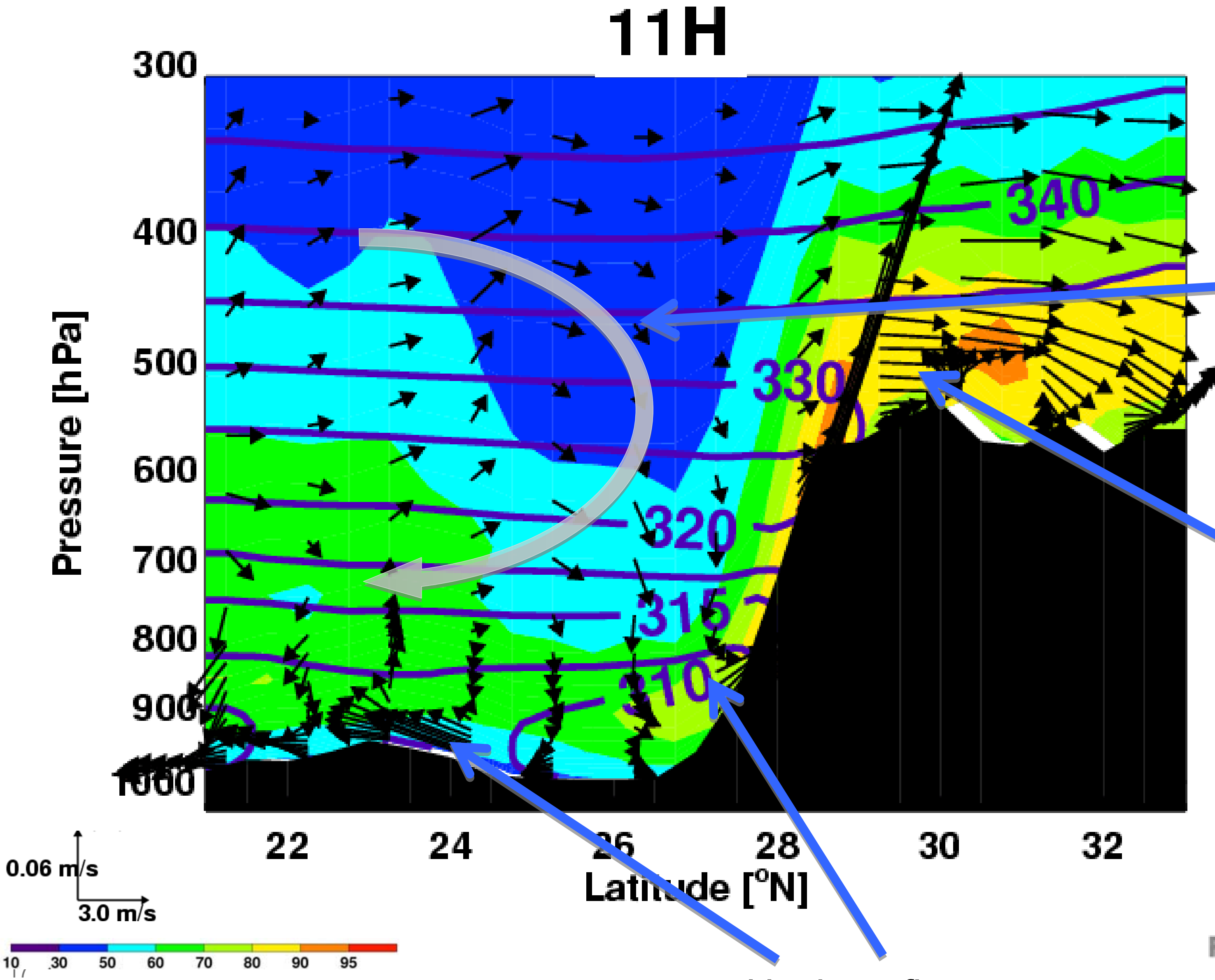
Dynamical and thermodynamical processes in the boundary layer near the Tibetan Plateau



Plateau-plain circulation weakens and retreats to the south

Developing a well-mixed boundary layer

Upslope flow

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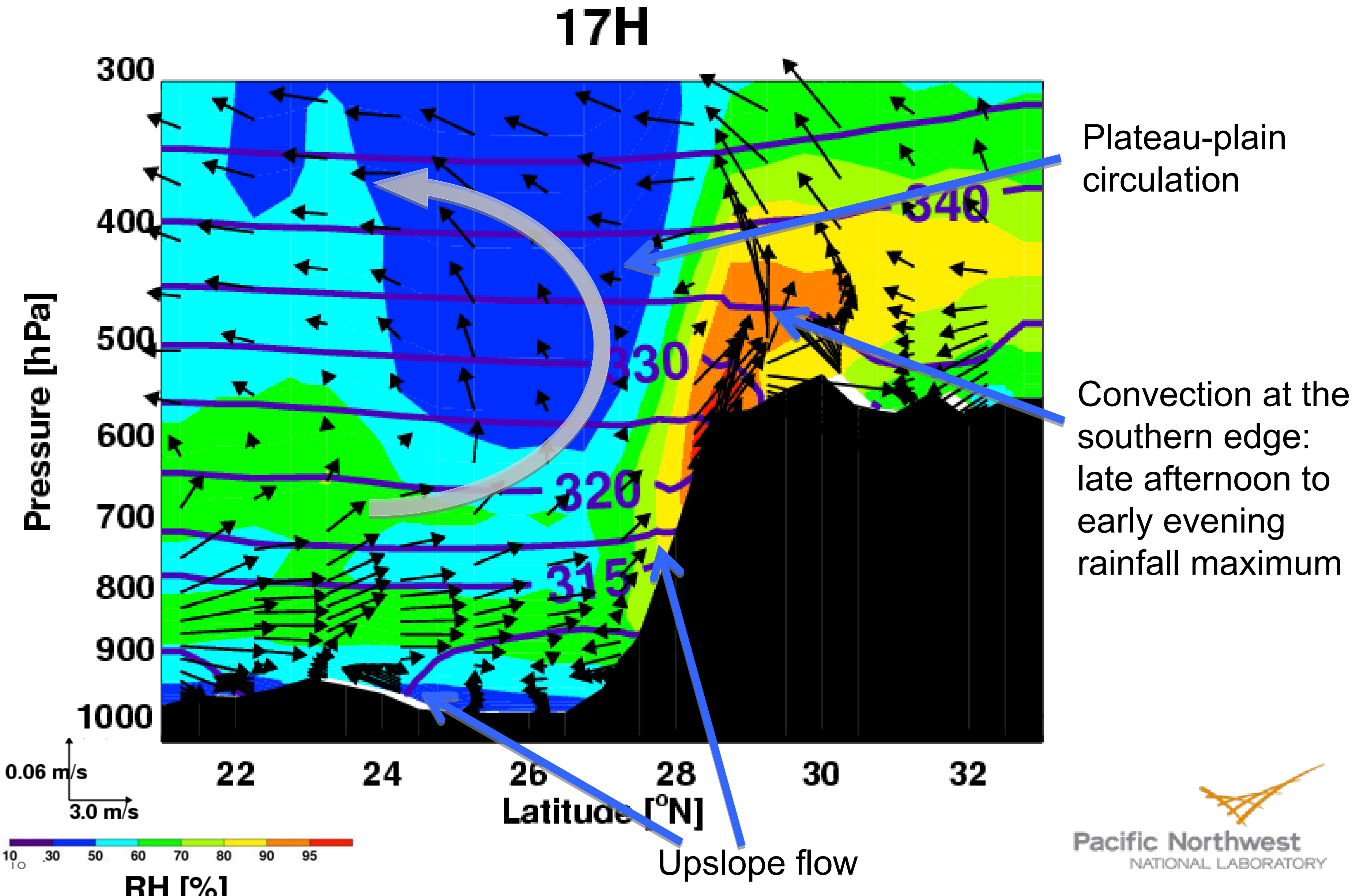
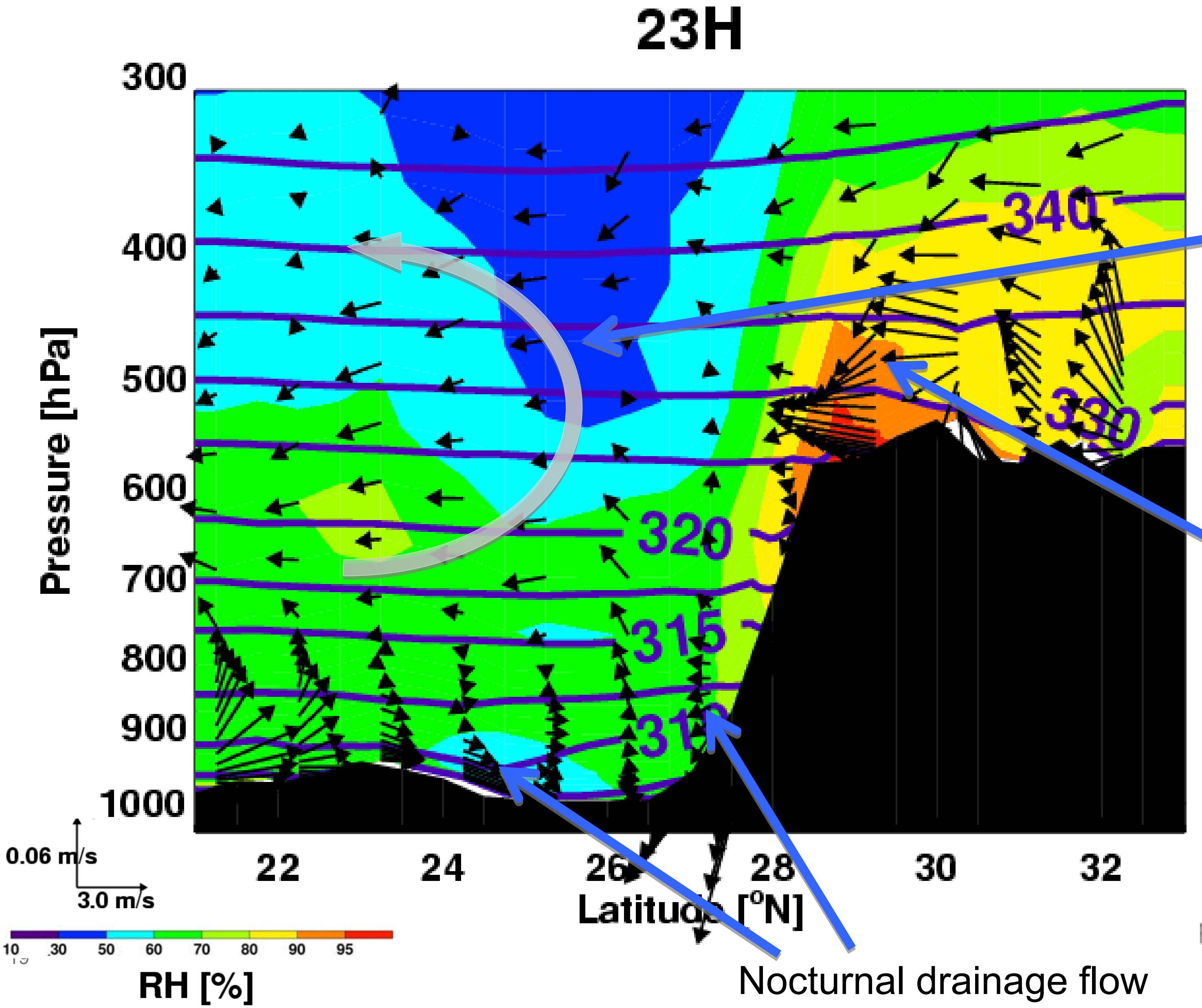
Dynamical and thermodynamical processes in the boundary layer near the Tibetan Plateau



Dynamical and thermodynamical processes in the boundary layer near the Tibetan Plateau



Plateau-plain circulation weakens and shifts to the south

Residual layer

Nocturnal drainage flow

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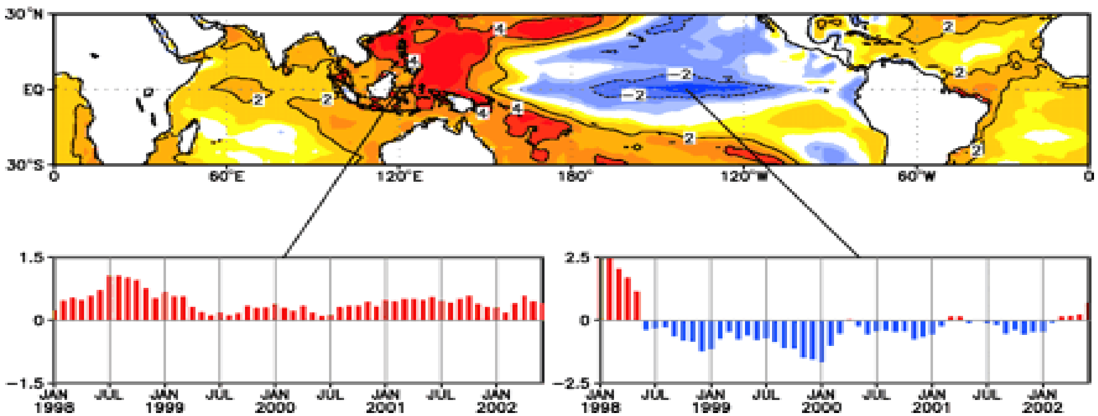
Future Plan

- Refine methods of assimilating precipitation and radiances to reduce water budget imbalance
- Conduct a 5-year pilot for 1998 – 2002
- Develop high resolution SST for the Indian Ocean
- Design techniques for assimilating aerosols
- Improve state estimation of the Northern Indian Ocean
- Generate a dynamics-thermodynamics consistent, high spatio-temporal resolution (30 km or less; 3 hours or less) reanalysis for 1979 – 2006 over the South Asian Monsoon land-ocean region

Droughts in the contemporary climate: A "perfect ocean" for drought?

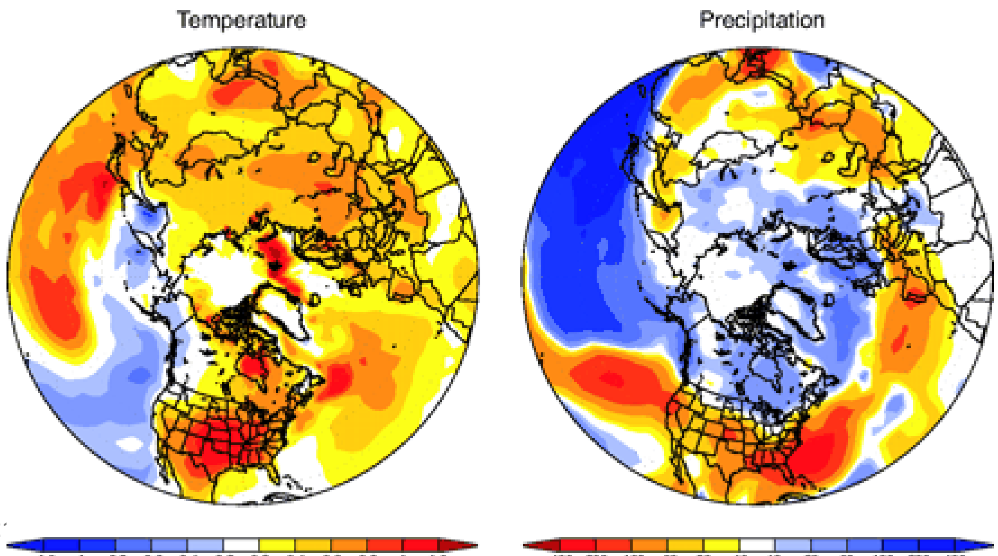
4-year-averaged SST during 1998-2002



1998 2002 1998 2002

During the 1998-2002 drought (US, southern Europe, SW Asia), cold SST in eastern tropical Pacific and warm SSTs in the western tropical Pacific were remarkably persistent.

Simulated T and P anomalies during 1998-2002



Simulated annually averaged T and P anomalies from 50-member ensemble by 3 GCMs each forced with the observed SST and sea ice anomalies of the 98-02 period.

Hoerling and Kumar (2003)

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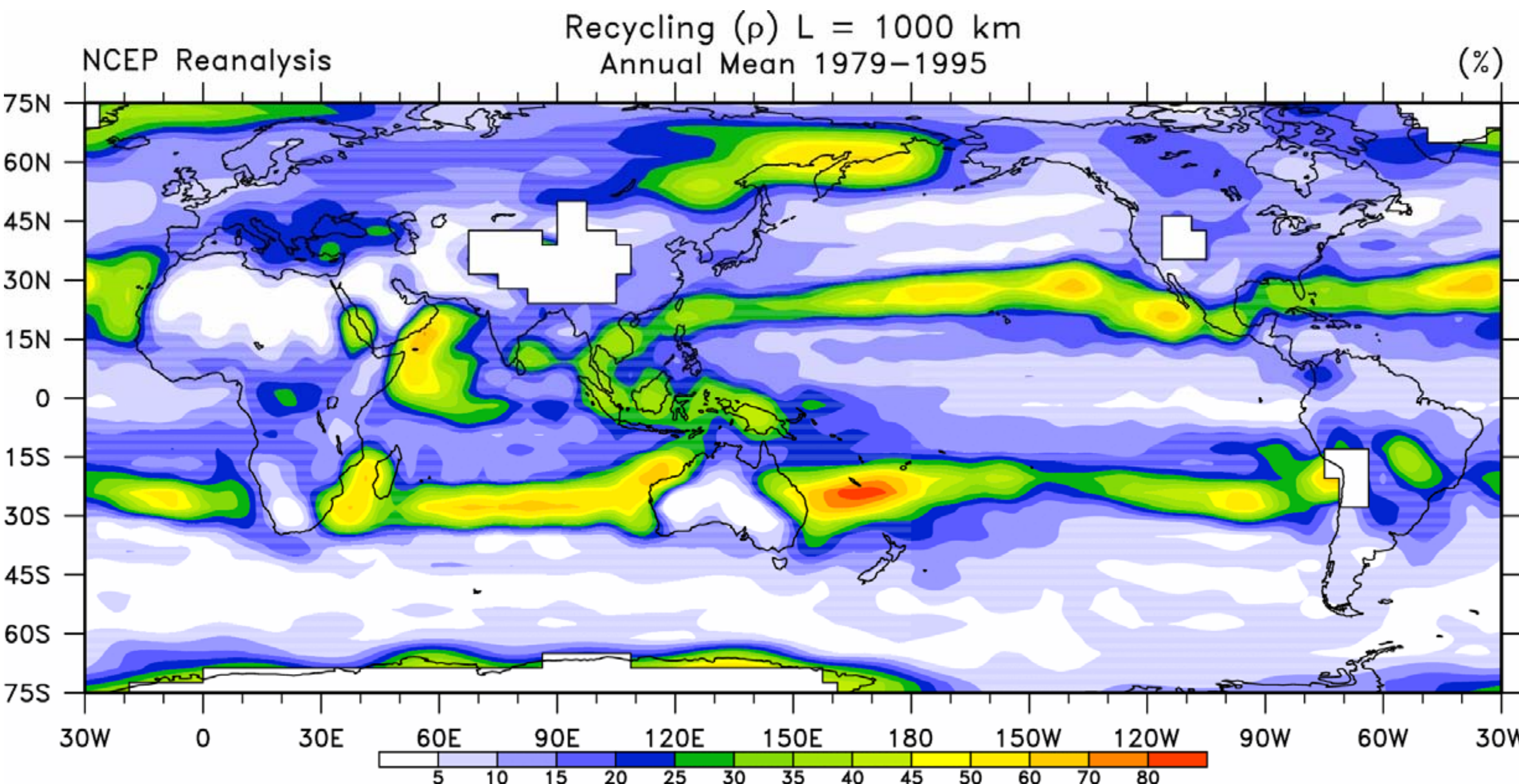
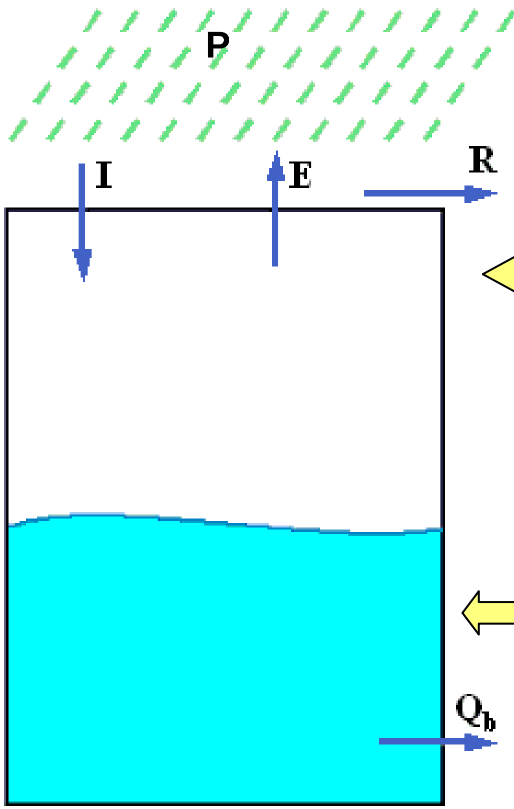
Local evaporation has important contributions to precip: What is the role land surface processes on droughts

- The recycling ratio measures the amount of local evaporation that contributes to precipitation
- At the 500 – 1000 km scale, the global recycling ratio is about 10% to 20%
- Mississippi basin: 21%; Amazon basin: 34%; Yangtze basin: 18%



Source: Trenberth 1999

A parameterization of surface and subsurface water interactions (Liang et al. 2003 JGR) has been implemented in an RCM



Change of soil moisture — Diffusion term — Drainage term

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left(D(\theta)\frac{\partial \theta}{\partial z} \right) - \frac{\partial K(\theta)}{\partial z} - sink(z,t)$$

Change of water table depth

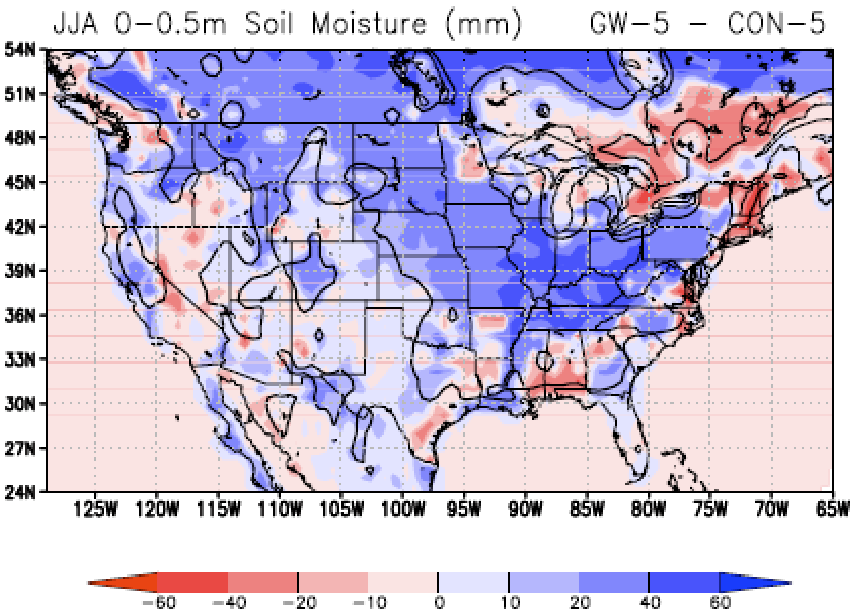
θ_s porosity
$n_e(t)$ effective porosity

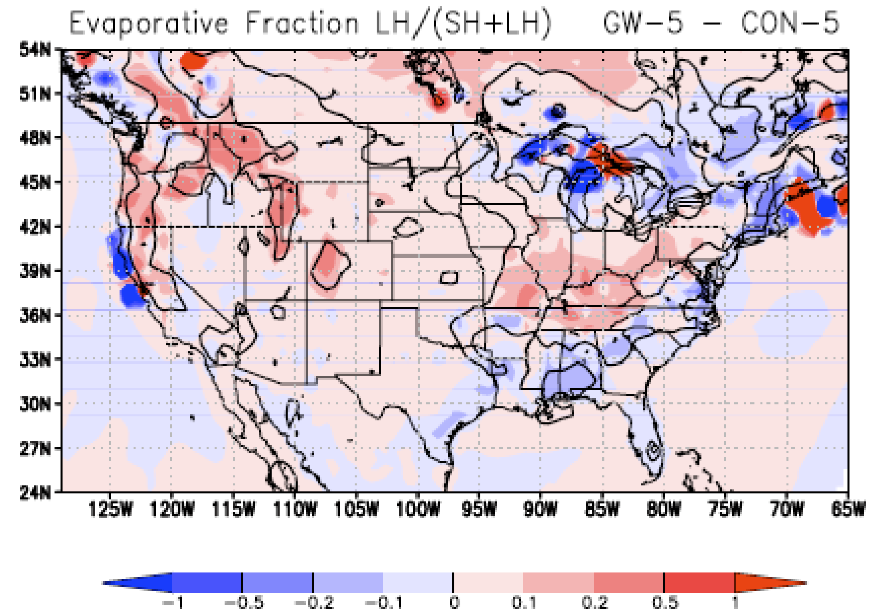
$$\alpha(t+\Delta t) - \alpha(t) = \frac{1}{\theta_s + n_e(t)} \times \left[\bar{\theta}(t+\Delta t) - \bar{\theta}(t) - \int_t^{t+\Delta t} (p - R - Q_b - E_t) \cdot dt \right]$$

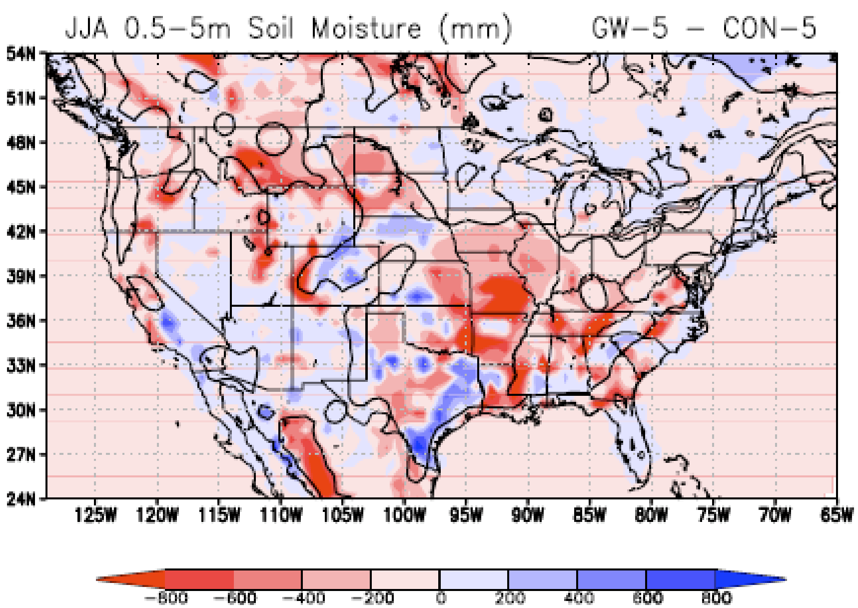
Change of total soil moisture in the unsaturated zone

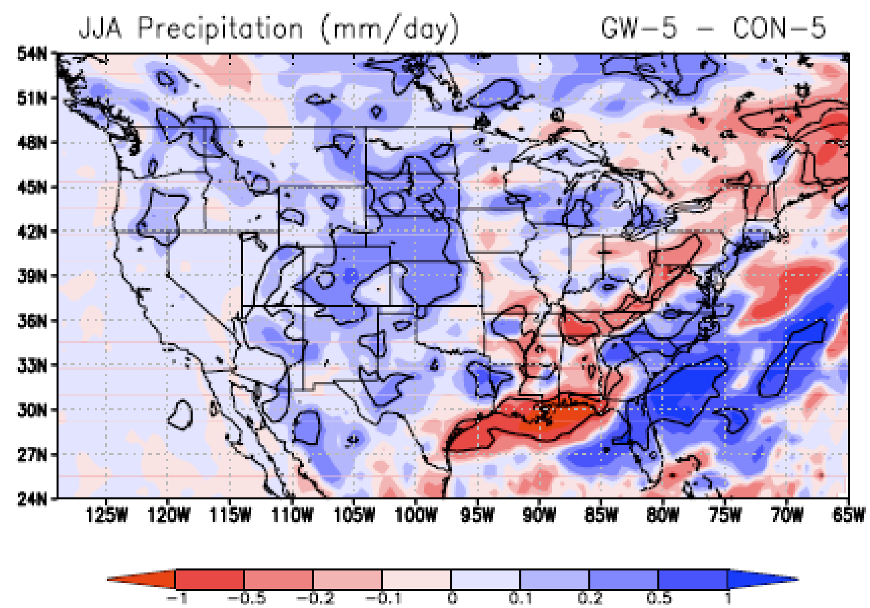
Net water recharge to groundwater body

Groundwater table dynamics alter the partitioning of surface and subsurface soil moisture, latent and sensible heat, and precipitation





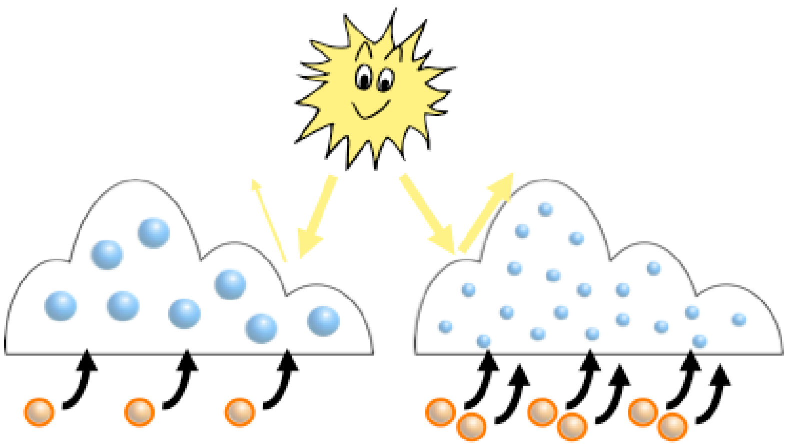




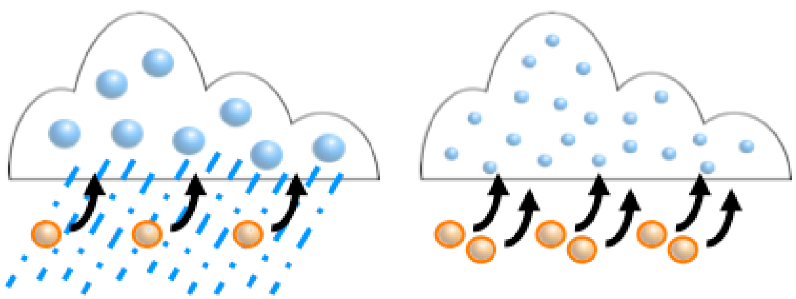
Research plan

- Simulations with a regional climate model that includes a dynamic groundwater table component show that climate and soil and vegetation properties have important control on the groundwater table
- Interactions between surface and subsurface hydrology modulate the partitioning of surface soil moisture and deep layer soil moisture to alter evapotranspiration, which acts to provide a feedback on clouds and precipitation
- Land use changes can alter groundwater table depth and modify land-atmosphere interactions
- Regional climate simulations will be performed over China to investigate the impacts of land use change on droughts

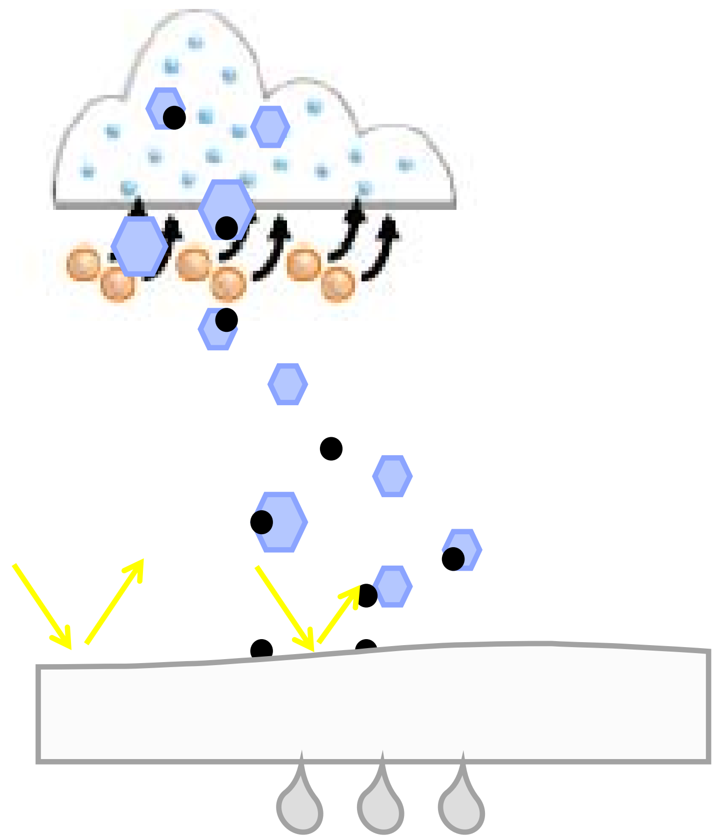
Aerosol Effects on the Hydrologic Cycle



First Indirect Effect:
Cloud Reflectivity



Second Indirect Effect:
Cloud Lifetime and Rain Properties

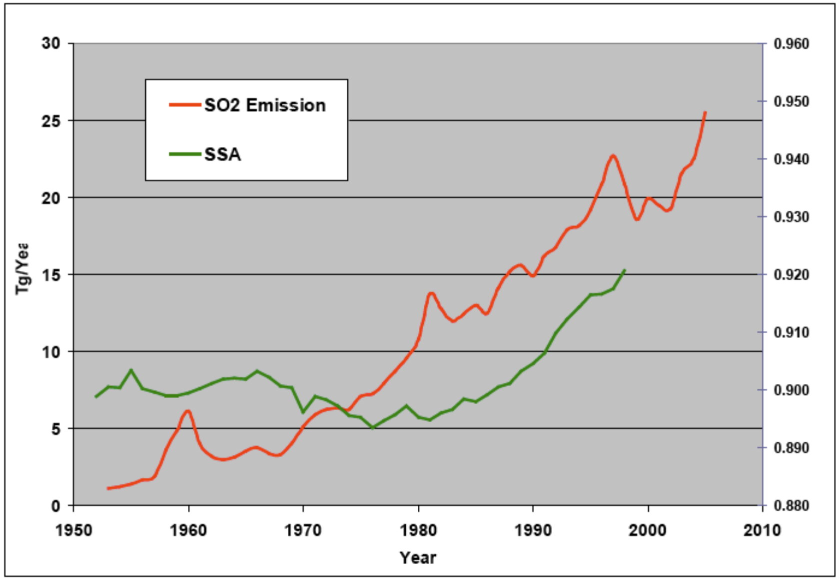


Soot Deposition on Snow:
Influence Both Energy and Water Cycles

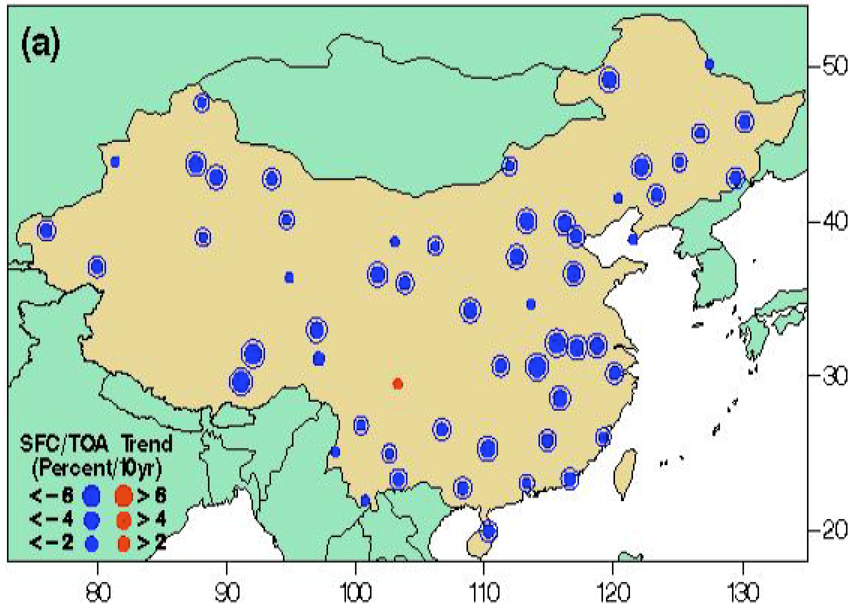
Aerosol effects in East Asia

- China has experienced significant changes in air quality – the emissions of fossil fuel sulfur dioxide have increased about nine-fold since 1950
- Aerosols can influence global and regional energy and water cycles through their interactions with radiation and cloud microphysical processes
- Our observational analyses have provided strong evidence of aerosol direct effects in China

Air pollution has been increasing

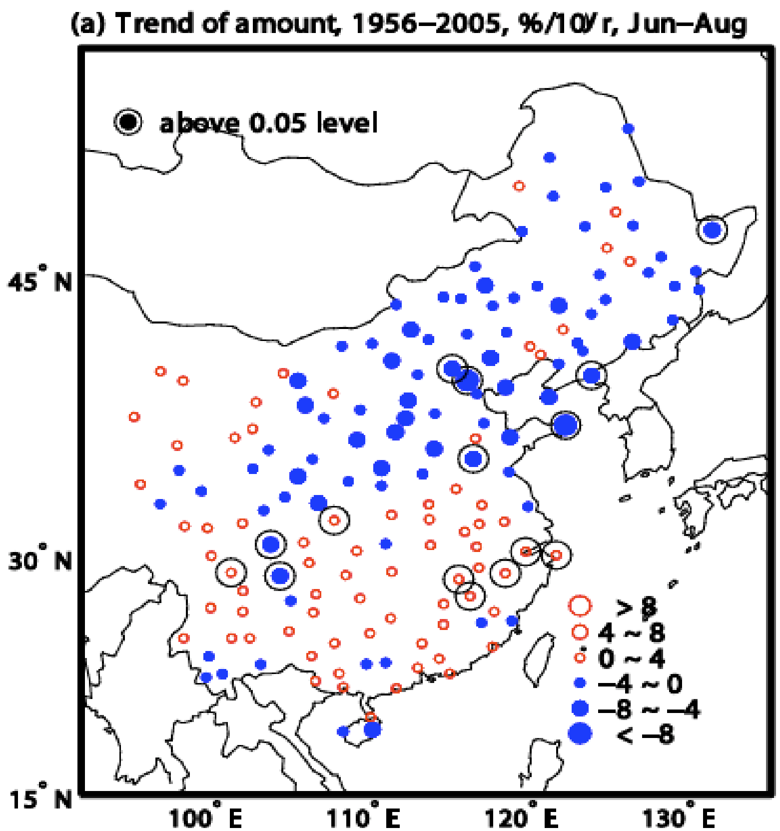


Global solar radiation under cloud free days has decreased

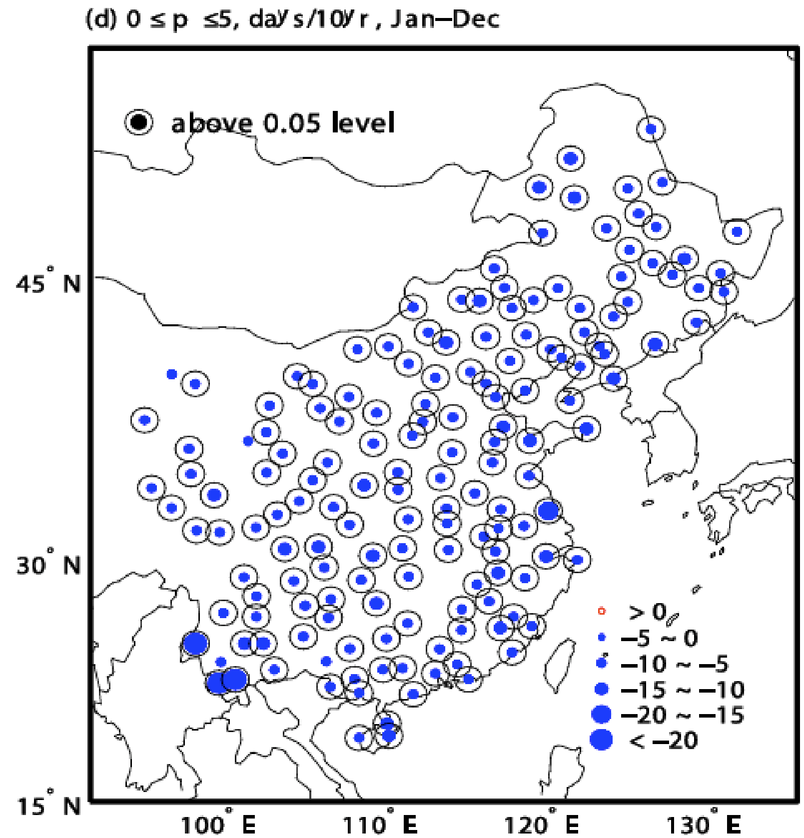


Aerosol effects on precipitation

Total precipitation exhibits the north drought – south flood trend

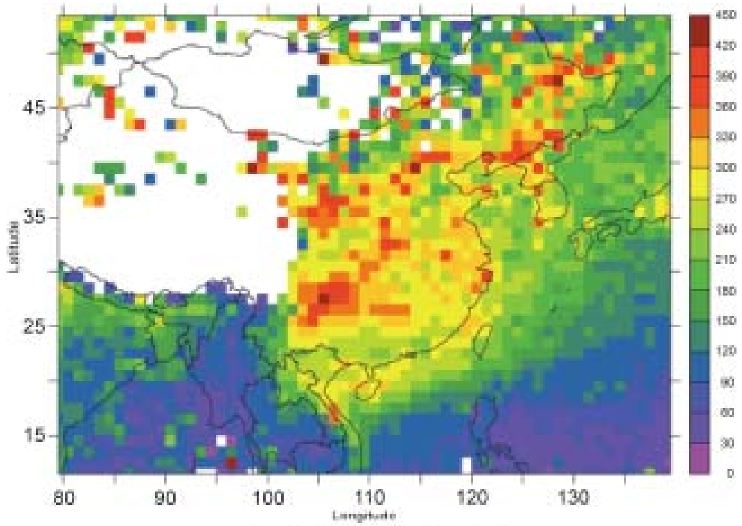


Light precipitation has, however, decreased uniformly in East China

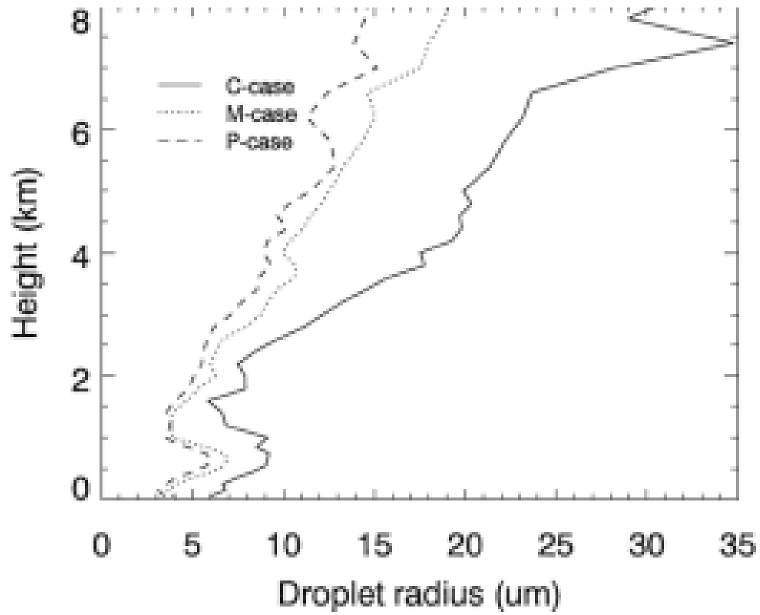


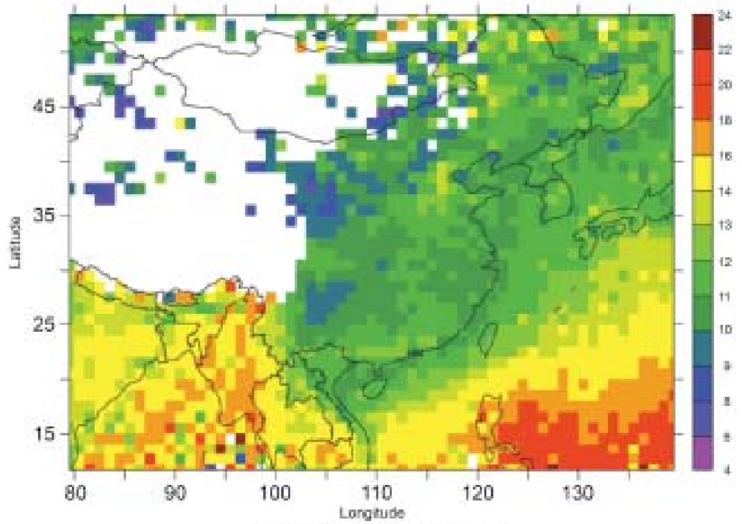
- How can we more firmly establish the relationships between aerosols and the observed climatic trends in China?
- Do climate models have adequate physics parameterizations to answer the above question, especially aerosol indirect effects?

Both satellite data and modeling results suggest that air pollution can reduce light precipitation by reducing cloud drop size and hence, precipitation efficiency

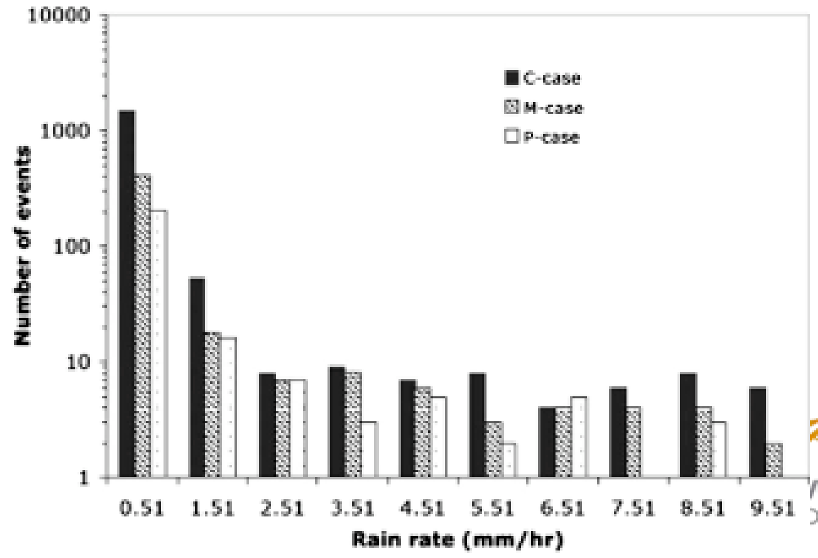


Mean CDNC (cm^--3)





Mean CERW (microns)



Future plan

- A detailed spectral bin microphysical (SBM) parameterization has been implemented in WRF
- Comparison of simulations using SBM and bulk microphysical parameterizations can provide guidance to improve the latter for assessing aerosol effects using climate models
- Regional climate simulations will be performed over Asia to estimate aerosol direct and indirect effects