MEETING SUMMARIES

BUILDING THE NEXT GENERATION OF CLIMATE MODELERS
Scale-Aware Physics Parameterization and the "Grey Zone" Challenge

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Climate system models have typically been restricted to grid resolutions from a few hundred kilometers down to a few tens of kilometers owing to computational constraints, and a representation of subgrid physical processes by parameterization is required. The continuing advances of science and technology are allowing larger computations and higher horizontal resolution for weather forecasting and climate models toward the kilometer scale. However, at resolutions ranging from 1 to 10 km, several physical processes are partially but not fully represented by the resolved dynamics and therefore still need to be partly parameterized in an appropriate way. The traditional scale separation assumptions between resolved and unresolved subgrid processes break down for this intermediate range of resolutions, known as the "grey zone," requiring the development of new parameterizations. To increase the knowledge and training of a new generation of researchers working on the development of climate models suitable for grey zone resolutions, the World Climate Research Programme (WCRP) promoted the

THE SECOND WORLD CLIMATE RESEARCH PROGRAMME SUMMER SCHOOL ON CLIMATE MODEL DEVELOPMENT: SCALE-AWARE PARAMETERIZATION FOR REPRESENTING SUBGRID-SCALE PROCESSES

WHAT: The Second WCRP Summer School brought together expert scientists to share knowledge with early career scientists on the latest developments in global atmospheric models with an emphasis on the so-called grey zone.

WHEN: 22–31 January 2018

WHERE: Cachoeira Paulista, São Paulo, Brazil

Second WCRP Summer School[1] on Climate Model Development: Scale-Aware Parameterization for Representing Subgrid-Scale Processes. A scientific committee evaluated a large number of applications and the potential relevance of each application to the summer school objectives was discussed. Throughout the selection process, the board considered the potential knowledge transfer as an important factor. In particular, improving and increasing climate modeling capabilities in developing countries was an additional aim of the summer school. Most of the 30 early career researchers (ECRs) selected came from

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[1] The school was hosted by the National Institute for Space Research, Center for Weather Forecasting and Climate Studies (INPE/CPTEC) in Cachoeira Paulista, São Paulo, Brazil.

the weather and climate communities in Argentina, Brazil, and Peru. Other selected participants came from Pakistan, India, and Japan. Full and partial financial support was offered to some candidates by WCRP and the Brazilian National Council for Scientific and Technological Development [Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq)]. The participants were encouraged to visit the precourse web page, which included lectures from the First WCRP Summer School on Climate Model Development: The Representation of Atmospheric Moist Processes. A basic knowledge of the representation of cloud and convective processes in climate models was a requirement for the 2018 school. Through 11 lecturers and 9 keynote speakers from Europe, the United States, and Brazil, the school offered 35 hours of topical presentations, including 6 remote talks and 14 hours of interactive practical activities. Online livestream content allowed for remote viewing of all presentations and discussions. A poster session with students' presentations brought together senior experts and ECRs and provided the opportunity to engage in scientific discussions around the ECR research topics. The school also included a presentation on the Young Earth System Scientists Community (YESS; www .yess-community.org) which illustrated possibilities and advantages for ECRs to become engaged in ECR networks.

KEY TOPICS. The themes of the school revolved around both the use of observations and a hierarchical modeling approach to improve physical process understanding, parameterization, and coupling to the dynamics in climate models (Fig. 1).

In the following, we outline highlights from the lectures and keynote talks.

Coupling between physics and dynamics. There are several challenges related to the coupling between physics and dynamics within each Earth system component, as well as challenges in the coupling between components (usually through a coupler). At the summer school we focused on the atmospheric component. The coupling between the dynamical core and physics tendencies computed by the parameterizations can be treated in many ways. It is important that budgets that are closed in the continuous equations of motion are also preserved in the discretization of those equations (e.g., the mass budget). In global coupled modeling it is important that the total energy budget is closed, which becomes more complex at higher resolutions for which a more comprehensive definition of energy that includes condensates is needed. Parameterizations need to be reformulated or adapted for a comprehensive conservation of the energy budget and the dynamical core needs to be consistent with the energy formulas used in physics, especially within the context of unstructured grids applied across scales. Practical activities included the evaluation of two different dynamical cores in a numerical weather prediction (NWP) and climate prediction setup by using a suite of simplified physical processes. The aim of the experiments was to analyze the conservation of important dynamical and physical properties in different dynamical cores and assess how idealized meteorological systems evolve with time. An idealized experiment with simplified moist physics was used to investigate the evolution of a baroclinic wave from small perturbations around an atmospheric steady state and to assess how the different dynamical cores kept the atmosphere in balance.

Turbulence and planetary boundary layers. Models solve filtered budget equations on a discrete grid, and their

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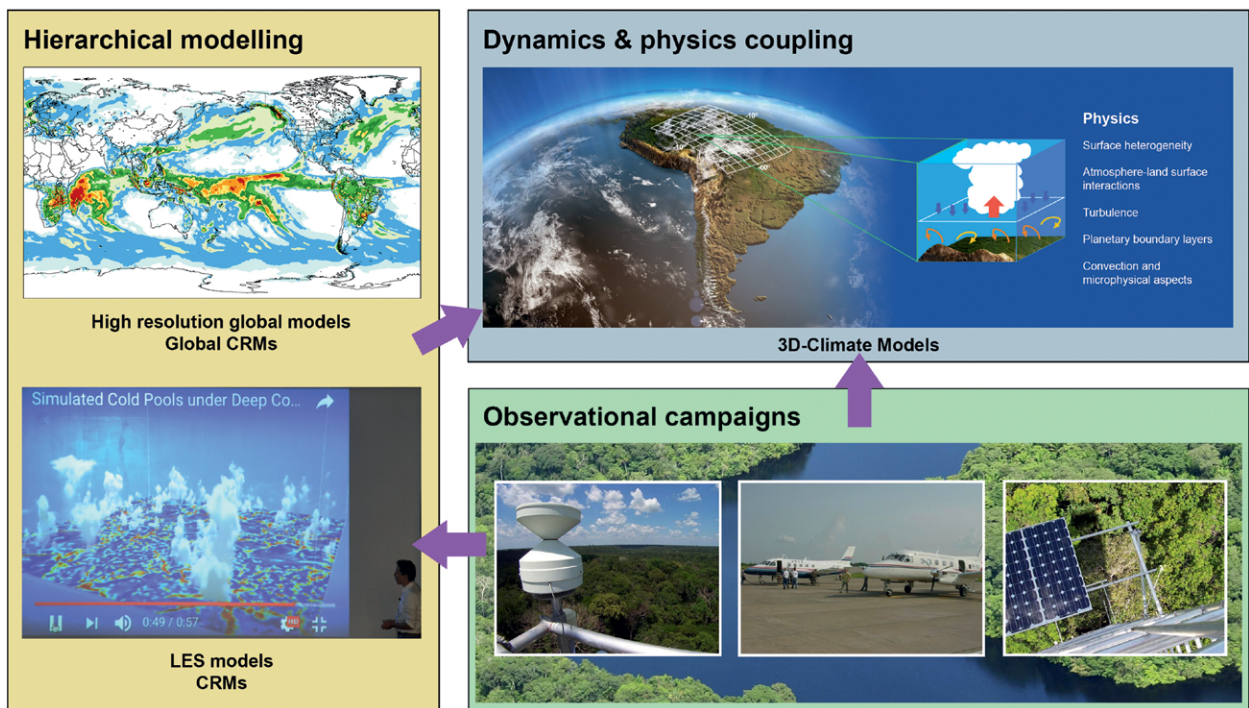**CORRESPONDING AUTHOR:** Ariane Frassoni, ariane.frassoni@inpe.br

Fig. 1. The themes of the second WCRP summer school: observational campaigns to support model development; hierarchical modeling using LES models, CRMs, high-resolution global models and global CRMs to better understand and improve dynamics, physical parameterizations, and their coupling in 3D climate models. (Figure courtesy of INPE/CPTEC; http://brams.cptec.inpe.br/; http://lba2.inpa.gov.br.)

subgrid parameterizations need to capture unresolved processes like convective transport and turbulence in the planetary boundary layer (PBL). For the PBL, turbulent mixing of momentum, heat, and moisture is commonly represented with an eddy diffusivity approach, whereas shallow and deep convective transports are commonly represented with a mass flux formulation. Given that the scales of the large PBL eddies are on the order of the boundary layer depth and similar to the shallow convection, models are increasingly using a combined eddy diffusivity mass flux approach in unified schemes. The scale dependency of the partitioning between resolved and subgrid transport by boundary layer turbulence and convective clouds becomes important in the grey zone for models approaching 1-km grid resolution where these phenomena are only partially resolved, and it is still an area of active research. Numerical tools such as cloud-resolving models (CRMs) and large-eddy simulation (LES) models together with single-column models (SCMs) are widely used to develop and improve physical parameterizations. As part of the practical exercises, students performed simulations of a dry convective boundary layer and the Barbados Oceanographic and Meteorological Experiment (BOMEX) shallow cumulus cloud case with the publicly avail-

able Dutch Atmospheric LES (DALES) model. This allowed the students to gain insight into the turbulent transports in these two distinct PBL regimes. In addition, the results were used to diagnose eddy diffusivity profiles and included exercises on mass-flux statistics from a conditional sampling of the 3D fields.

Deep convection and microphysics. Generally, classical methodologies for the parameterization of subgrid-scale convection based on mass-flux-type schemes consider properties like updrafts and compensating subsidence, with a very simplified representation of the microphysics. With increasing horizontal resolution, the hypotheses that form the basis of these schemes become increasingly less valid. In grey zone resolutions, there is a need for scale-aware schemes in which they can self-adjust in situations where convective circulations are being explicitly resolved, entirely or in part, leaving the cloud microphysics to take over the production of the convective rainfall and the vertical distribution of mass, momentum, and energy. One of the strategies for conventional methodologies to become scale aware is through the decrease of the vertical eddy transport term as the area occupied by convection increases. An alternative approach does not concentrate the vertical eddy transports to just

one grid cell but simply distributes the environmental subsidence over the neighboring grid cells. With increased horizontal resolution, more of the vertical motion becomes resolved and the microphysics plays an increasingly important role in climate models. In particular, as deep convective motions become resolved through the grey zone, more complexity is required, including explicit treatment of graupel and hail associated with strong convective updrafts. It is recognized that microphysics is important in the treatment of cloud–aerosol–radiative interactions and in determining precipitation formation and cloud lifetime. However, there are still many uncertainties associated with microphysics of clouds and precipitation, and there is a continuing need for observations, theory, and detailed process studies to improve its representation in numerical models. As part of practical activities students performed simulations using the Centro de Previsão do Tempo e Estudos Climáticos (CPTEC) SCM to test convective parameterizations and microphysics under different cloud conditions from BOMEX, the Tropical Ocean Global Atmosphere (TOGA) program, and the Southern Great Plains (SGP) Atmospheric Radiation Measurement (ARM) field experiments. The exercise allowed students to gain insight into how sensitive the representation of deep convection and precipitation is to model resolution and physics complexity.

Land surface interaction. Land surface models require a set of physics and model parameters, atmospheric forcings, land datasets, initial land states, and land data assimilation. A complete characterization of the land surface is necessary since many studies show evidence of the land surface providing predictive skill on both weather and climate time scales. However, several surface processes are not yet constrained by observations, and further research and observational studies are required to support model development. One example is the representation of surface stress in models, which is associated with resolved and subgrid-scale orography and surface roughness effects. More generally, as weather and climate models begin to represent the Earth system in its entirety, additional communities must be more fully included in land model development. Examples are hydrology and ecology, with corresponding upgrades to the models to describe, for example, the complexity of surface and subsurface water movement, and the broad range of biogeochemical cycles. All of these branches, operating on multiple time and spatial scales, require the necessary upscaling and downscaling to connect the various Earth system components. Also of considerable importance in the future is the human influence on land processes and water (management), including the effects of expanding urban regions.

Observation field campaigns. Lectures focusing on observational field campaigns to improve the modeling of the climate system highlighted the extensive projects conducted in South America in recent decades, including the Anglo–Brazilian Amazonian Climate Observation Study (ABRACOS), the Amazon Boundary Layer Experiment (ABLE), and the Large-Scale Biosphere–Atmosphere Experiment in Amazonia (LBA) initiated in the 1980s and mid-1990s, and more recently the Green Ocean Amazon (GoAmazon) experiment. These campaigns were conducted with the goal of improving our knowledge of the role of tropical areas in the global climate, and they provide a rich dataset for use in the characterization and understanding of the cloud dynamics, thermodynamics, cloud–aerosol–radiation interactions, and microphysical processes across the Amazon basin. The observational information can be used in evaluating hierarchical modeling and improving physical parameterizations. Several students and ECRs have benefited from such field campaigns in South America, both by direct involvement in the organization of in situ data collection and by using the data for their research.

MAIN OUTCOMES. On the last day of the school, an evaluation form was given to all those enrolled, with scoring from grade 1 (not efficient) to grade 6 (highly efficient). The topics to be evaluated included precourse preparation; goals of the school, expectations, and relevance; content; school design; opinions on the speakers; and questions in general. The mean score was 5.2 (efficient). Students highlighted the high quality of the lectures, although some found they assumed too much background knowledge and were pitched at too high a level. However, students found the practical exercises were effective in increasing their understanding and overall comprehension. The school live stream allowed a larger number of students to participate remotely (recordings are available at the INPE/Grey channel, www.youtube.com /playlist?list=PLzU9Iqk8MaUtmbWYbVcVVwRZS _kWwfSba) The recordings allow access to the summer school lectures for the future, supporting the training of other communities, adding value to the WCRP training activities, and providing a growing legacy of the WCRP Summer School on Climate Model Development series.

The school covered many aspects of Earth system simulation, including the coupling between physics

and dynamics, turbulence and the PBL, land surface interaction, and observational studies in support of model development. The global climate modeling community is growing, and the focus of the 2018 summer school on scale-aware physics parameterization and the grey zone challenge continues the advancement of scientific understanding for the next generation of climate modeling systems.