Influence of various parameters of INM RAS climate model on the results of extreme precipitation simulation

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Abstract. The results of simulation of extreme weather indices of modern climate by two versions of the INM RAS climate model (INMCM4, INMCM5) are considered. It is shown that the INMCM5 model simulates most of the temperature and average precipitation related indices better, but the simulation results of extreme precipitation related indices are worse. Various precipitation related physical factors in the model are analyzed. A parameterization of vertical mixing of the horizontal velocity components due to large-scale condensation, as well as air resistance acting on falling precipitation, is implemented in the INMCM5. The corresponding model parameters are adjusted. The effect of the adjustments on the simulation results of extreme indices is presented.

1. Introduction

Modern models of the Earth’s climate can reproduce not only the average climate condition, but also extreme weather and climate phenomena. Therefore, there arises the problem of comparing climate models for observable extreme weather events.

In [1, 2], various extreme weather and climatic situations are considered. According to the paper, 27 extreme indices are defined, characterizing different situations with high and low temperatures, with heavy precipitation or with absence of precipitation.

The results of simulation of the extreme indices with the INMCM4 [3] climate model were compared with the results of other models which took part in the CMIP5 project (Coupled Model Intercomparison Project, Phase 5) [2]. The comparison demonstrates that this model performs well for most indices except for those related to daily minimum temperature. For those indices the model shows one of the worst results.

The parameterizations of physical processes in the next model version, INMCM5, were replaced or tuned [4, 5], so that changes in the extreme indices simulation are expected.

The simulation results were compared to the ERA-Interim [6] reanalysis data, which were considered as the observational data for this study. Indices averaged for the 1981–2010 year range were compared. Mann-Whitney test with 1% significance level was used to examine where changes are significant.

To evaluate the quality of simulation of extreme weather phenomena, the extreme indices were calculated [7] using the results of computations performed by two versions of the INM RAS climate
model (INMCM4 and INMCM5) and the ERA Interim reanalysis. We took the root mean square deviation of the index value computed from the modeled and reanalysis data as the measure of simulation quality. The mean is averaged over the land.

Table 1. Root mean square deviation of temperature indices for models: INMCM4, INMCM5, INMCM5VM ($A_0 = 7.5, C_{INC} = 3$), INMCM5AR ($W_L = 5$ m/s, $W_S = 0.5$ m/s, $A_0 = 8, C_{INC} = 2$) compared to ERA-Interim reanalysis.

| Index name               | Label, unit | INM CM4 | INM CM5 | INM CM5VM | INM CM5AR |
|--------------------------|-------------|---------|---------|-----------|-----------|
| Max $T_{max}$            | TXx, K      | 4.6     | 3.7     | 3.5       | 3.5       |
| Min $T_{max}$            | TXn, K      | 5.4     | 4.8     | 5.4       | 5.4       |
| Max $T_{min}$            | TNx, K      | 3.0     | 2.3     | 2.3       | 2.4       |
| Min $T_{min}$            | TNn, K      | 13.4    | 6.7     | 7.4       | 7.7       |
| Diurnal temperature range| DTR, K      | 6.4     | 2.8     | 2.7       | 2.8       |
| Growing season length    | GSL, days   | 24      | 15      | 15        | 15        |
| Frost days               | FD, days    | 58      | 20      | 21        | 22        |
| Ice days                 | ID, days    | 15      | 11      | 11        | 12        |
| Summer days              | SU, days    | 45      | 40      | 37        | 37        |
| Tropical nights          | TR, days    | 99      | 48      | 51        | 57        |
| Cold days                | TX10p, %    | 1.2     | 1.0     | 1.2       | 1.1       |
| Cold nights              | TN10p, %    | 1.1     | 0.9     | 1.2       | 1.1       |
| Warm days                | TX90p, %    | 1.7     | 1.7     | 1.9       | 1.8       |
| Warm nights              | TN90p, %    | 1.7     | 1.7     | 1.7       | 1.7       |
| Warm spell duration      | WSDI, days  | 4.7     | 4.9     | 4.7       | 4.4       |
| Cold spell duration      | CSDI, days  | 3.2     | 3.1     | 3.4       | 3.1       |

Table 2. Root mean square deviation of precipitation indices for models: INMCM4, INMCM5, INMCM5VM ($A_0 = 7.5, C_{INC} = 3$), INMCM5AR ($W_L = 5$ m/s, $W_S = 0.5$ m/s, $A_0 = 8, C_{INC} = 2$) compared to ERA-Interim reanalysis.

| Index name               | Label, unit | INM CM4 | INM CM5 | INM CM5VM | INM CM5AR |
|--------------------------|-------------|---------|---------|-----------|-----------|
| Number of wet days       | R1mm, days  | 41      | 40      | 39        | 39        |
| Heavy precipitation days | R10mm, days | 32      | 26      | 24        | 22        |
| Very heavy precipitation days | R20mm, days | 9.8     | 6.2     | 6.5       | 6.3       |
| Consecutive dry days     | CDD, days   | 35      | 37      | 38        | 36        |
| Consecutive wet days     | CWD, days   | 46      | 30      | 27        | 27        |
| Simple daily intensity   | SDII, mm/day| 1.7     | 1.5     | 1.5       | 1.4       |
| Max 1 day precipitation  | RX1day, mm  | 19      | 19      | 17        | 15        |
| Max 5 day precipitation  | RX5day, mm  | 28      | 43      | 40        | 36        |
| Very wet days precipitation | R95p, mm   | 120     | 130     | 130       | 120       |
| Extremely wet days precip| R99p, mm    | 57      | 53      | 49        | 48        |
| Total wet-day precipitation | PRCPTOT, mm | 550     | 480     | 470       | 450       |

Tables 1 and 2 present the names of extreme indices related to temperature and precipitation, their labels and measurement units, as well as the land only averaged standard deviations for these indices between the ERA-Interim reanalysis and different versions of the INM RAS climate model.

Table 1 shows that the simulation of almost all temperature indices has improved in the INMCM5 compared to INMCM4. In particular, the simulation of the following extreme indices related to the minimum daily temperature improved significantly (by 37–56%): the annual daily minimum temperature (TNn), the number of frost days (FD) and tropical nights (TR), the diurnal temperature range (DTR), and the growing season length (GSL).
Table 2 shows that the simulation of the number of heavy (R10mm) and very heavy (R20mm) precipitation days, consecutive wet days (CWD), simple daily intensity (SDII), and total wet-day precipitation (PRCPTOT) noticeably improved in INMCM5. At the same time, the simulation of indices related to the intensity (RX5day) and the amount (R95p) of precipitation on very rainy days became worse.

Figures 1a,b–3a,b show the spatial distribution of max 1 day (RX1day) and 5 day precipitation (RX5day) according to ERA-Interim reanalysis and their deviations from reanalysis according to INMCM5 data.

Figures 1a,b–3a,b show that INMCM5 overestimates RX1day and RX5day in Central and Eastern North America, the Amazon basin, South Africa, South, East, Southeast Asia and Australia, as well as underestimates max 1 day and 5 day precipitation in West Africa. Thus, INMCM5 overestimates the intensity of precipitation on very rainy days, especially in those regions where it is large according to the ERA-Interim reanalysis data.

To improve the simulation of extreme precipitation by the INMCM5 model, the following physical processes were considered: evaporation of precipitation in the upper atmosphere; mixing of horizontal velocity components due to large-scale condensation and deep convection; air resistance acting on falling precipitation particles.

2. Evaporation of precipitation in the atmosphere

In the INMCM5 model precipitation is formed as a result of balancing of two processes: the conversion of cloudy moisture into precipitation and the evaporation of falling precipitation [8].

The evaporation rate of precipitation in the model cell is determined by

\[ E_p = 5.44 \times 10^{-4} (1 - a)(q_{\text{max}} - q) \left( \frac{P \sqrt{p / p_s}}{5.9 \times 10^{-3}} \right)^{1/2} \]

where \( a \) is the fraction of the cell occupied with clouds, \( q_{\text{max}} \) is the maximal specific humidity at the current cell temperature, \( q \) is the specific humidity in the cell, \( P \) is the total precipitation flux from above (kg m\(^{-2}\) s\(^{-1}\)), \( p \) is the pressure in the cell and \( p_s \) is the pressure at the surface level. Here \( E_p \) cannot exceed the \( E_p^{\text{max}} \) value at which all water falling as precipitation from cloud moisture evaporates.

To estimate the effect of evaporation in the upper atmosphere on the formation of extreme precipitation, the dependence (1) was simplified to proportional one

\[ E_p = KE_p^{\text{max}}, \quad K = \text{const}. \]

With this simplified formula and the proportionality coefficient taken to be \( K = 0.2 \) and \( K = 1 \), computations for three model years were carried out. This was done to test the sensitivity of the model simulation of max 1 day precipitation (RX1day) to changes in the precipitation evaporation rate in the upper atmosphere. Figures 1c, 1d show deviations of RX1day for the INM RAS climate model with changed evaporation rate for two different values of \( K \) compared to the original INMCM5 model.

Note that for \( K = 0.2 \) (Figure 1c) there is both an overestimation of RX1day in the Amazon basin, South Africa, and East Asia and its underestimation in Central North America, South America, and South Asia. In Australia, significant overestimation of max 1 day precipitation in some areas is compensated by an equally significant understatement in the others. In general, it can be noted that at \( K = 0.2 \) the quality of reproducing the RX1day index has not changed.

Figure 1d for \( K = 1 \) illustrates significant overestimation of RX1day in the Amazon basin, South Africa, South and Southeast Asia and Australia, that is, in those regions where the max 1 day precipitation according to INMCM5 is overestimated compared to the ERA-Interim reanalysis data. Thus, with \( K = 1 \) the positive RX1day simulation error only increased.

Thus, changing the precipitation evaporation rate in the upper atmosphere only led to an increase in max 1 day precipitation in regions where, according to INMCM5, it was already too high compared to the ERA-Interim.
Figure 1. (a) RX1day index values averaged over 1979–1981 according to ERA-Interim data. (b–d) Deviations of the same average computed from data by INMCM5 model and its modification with \( K = 0.2 \) and \( K = 1 \).

3. Vertical mixing of horizontal velocity components

Both large-scale condensation and deep convection cause vertical motion, which redistributes the horizontal momentum between the nearby air layers.

The implementation of mixing due to large-scale condensation was added to the model. For two vertically adjacent cells the mixing is produced by the formulas

\[
\frac{\phi_k - \phi_{k+1}}{\Delta t} = \alpha_{k+1/2} (\phi^\text{avg}_{k+1/2} - \phi_k),
\]

\[
\frac{\phi_{k+1} - \phi_{k+1}}{\Delta t} = \alpha_{k+1/2} (\phi^\text{avg}_{k+1/2} - \phi_{k+1}),
\]

where \( \phi \) is either of the horizontal velocity components, \( k, k + 1 \) are adjacent vertical level numbers, \( \phi^\text{avg}_{k+1/2} \) is the value between \( \phi_k \) and \( \phi_{k+1} \) averaged over the sigma-coordinate, \( \alpha_{k+1/2} = \min(\Delta t^{-1}, A_0 P_{k+1/2}) \) is the mixing speed, \( \Delta t \) is the time step, and \( P_{k+1/2} \) is the precipitation flux from above. The mixing speed is artificially limited by \( \Delta t^{-1} \) to guarantee numerical stability of the procedure. The parameter \( A_0 \) is a fixed value chosen from the \( 1 \div 10 \text{ m}^2 \text{ kg}^{-1} \) range.

A similar procedure is carried out to take into account mixing associated with deep convection. The differences are that it is performed in the region between the lower and upper convection boundaries, and the mixing rate \( \beta \) is calculated by the formula
Here $\tau_{\text{HG}} = 12$ h is the characteristic convection time, $C_{\text{INC}}$ is a dimensionless constant parameter in the $1 \div 3$ range, $P_{\text{CV}}$ is the precipitation amount due to deep convection, $Q_{\text{TOT}}$ is the total amount of moisture in the convective region.

To adjust the parameter $A_0$ (which is responsible for mixing horizontal velocity components due to large-scale condensation), a number of short-term computations with different $A_0$ values in the $[1; 10]$ interval were carried out. The optimal $A_0$ value which minimizes the standard deviation from the reanalysis data for the RX1day and RX5day indices was found to be $A_0 = 7.5$. The parameter $C_{\text{INC}}$, which is responsible for mixing horizontal velocity components due to deep convection, was optimized with $A_0$ being fixed at 7.5. The optimal value for $C_{\text{INC}}$ was found to be 3.

For short we will refer to the INMCM5 version with these changes as INMCM5VM (INMCM5 Velocities Mixing).

After these parameters were tuned, a long-term computation was performed. The computed data were used to calculate the extreme indices. Table 1 shows that in the model with vertical mixing of the horizontal velocity components the quality of simulation of most of the temperature extreme indices either improved slightly or did not change in comparison with INMCM5. Exceptions are the annual minimum of the maximum daily temperature (TXn), the annual minimum of the minimum daily

$$\beta = \min \left( \frac{1}{\Delta t}, \frac{C_{\text{INC}} \cdot P_{\text{CV}}}{\tau_{\text{HG}} \cdot Q_{\text{TOT}}} \right).$$

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure2}
\caption{(a) RX1day index values averaged over 1981–2010 according to ERA-Interim data. (b-d) Deviations of the same average obtained from INMCM5, INMCM5VM, and INMCM5AR data. Statistically insignificant deviations are presented as white.}
\end{figure}
temperature (TNn), the number of frost days (FD) and tropical nights (TR), and the cold spell duration (CSDI): the simulation of these indices in INMCM5VM worsened by 5–13 % compared to INMCM5.

Table 2 shows that the quality of the simulation of the R1mm, R10mm, CWD, RX1day, RX5day and R99p indices improved in INMCM5VM by 2–10 % compared to INMCM5. However, for the R20mm and CDD indices the standard deviation from the reanalysis data increased by 3–5 %.

Figures 2c, 3c show the spatial distribution of deviations for max 1 day (RX1day) and 5 day (RX5day) precipitation between INMCM5VM from INMCM5. The model with the adjusted vertical mixing of horizontal velocity components compared to INMCM5 significantly underestimates the RX1day in Australia and slightly underestimates the RX1day in South America, South Africa, South, East and South-East Asia. Also INMCM5VM significantly underestimates RX5day in East Asia and Australia compared to INMCM5, and also slightly underestimates RX5day in South America, South Africa, South and Southeast Asia.

Therefore, adjusting the vertical mixing parameters significantly reduces the overestimation of RX1day and RX5day observed in INMCM5 in South Africa, East Asia, and Australia and, in general, leads to an improvement in the quality of extreme indices related to the precipitation amount and intensity on very rainy days simulation, although not as significant as necessary. At the same time, a significant overestimation of the RX1day, RX5day indices in the Amazon basin, South and Southeast Asia, as well as their underestimation in West Africa remains.

4. Air resistance acting on falling precipitation particles

Since precipitation particles (water droplets or ice crystals) move in the surrounding air, a drag force arises that carries the air along with the particles. This resistance force can be included in the right-hand side of the momentum balance equation, which is part of the atmosphere hydrothermodynamic system of equations. Accurate accounting for the effect of this force requires numerical solving of an additional Poisson-type equation.

On the other hand, if we consider the air-precipitation system, in it the drag force is internal and does not contribute to the total momentum of the system. The atmosphere hydrothermodynamic equations remain valid if the air density is replaced by the density of the air-precipitation mixture.

In the model, this additional precipitation density is obtained as the ratio of the precipitation flux to the steady velocity of falling of precipitation particles:

\[ \Delta \rho = \frac{P}{W_{\text{prec}}} \].

The range of the possible falling velocities is quite large and, therefore, in the calculation they were fixed with some constant values, different for water droplets and ice crystals.

The atmosphere dynamic equations used in the INMCM5 model do not contain the density in explicit form; instead it is expressed in terms of temperature and pressure from the ideal gas law:

\[ \rho = \frac{P}{RT} \].

Thus, the density in the equations is uniquely determined by the temperature. Therefore, before calculating the solution of the atmosphere dynamic equations at the next step, the temperature in the model is corrected by

\[ \Delta T = -T \frac{\Delta \rho}{\rho} = -\frac{RT^2}{P} \Delta \rho, \]

and after calculating the solution at this step, the inverse correction for the same \( \Delta T \) value is made. Since the relation

\[ \frac{\Delta T}{T} = -\frac{\Delta \rho}{\rho} \]

is valid only for small \( \Delta \rho \), the following restriction is also added to the model:
Since the temperature correction interferes with other processes in the model, it is only used in the atmosphere dynamic equations to determine the divergence of the horizontal velocity.

For short, we will refer to the INMCM5 model version with the air resistance and vertical mixing of the horizontal velocity components as INMCM5AR (INMCM5 Air Resistance).

During the computations the precipitation falling velocities were fixed at $W_L = 5$ m/s for liquid precipitation (water droplets) and $W_S = 0.5$ m/s for solid precipitation (ice crystals). The parameters $A_0$ and $C_{INC}$ were retuned again for this model, and the optimal values for them were found to be $A_0 = 8$ and $C_{INC} = 2$.

![Figure 3](image_url)

Figure 3. (a) RX5day index values averaged over 1981–2010 according to ERA-Interim data. (b-d) Deviations of the same average obtained from INMCM5, INMCM5VM, and INMCM5AR data. Statistically insignificant deviations are presented as white.

Table 1 shows that in the model with air resistance acting on falling precipitation particles the quality of simulation of most temperature-related extreme indices became worse by 9–19% compared to INMCM5. The exception is the annual maximum of daily maximum temperature (TXx), the number of summer days (SU), and the warm spell duration (WSDI): the error in reproducing these indices decreased by 5–10%. The reason for the increase in the error of simulation of the temperature indices is probably the inaccurate temperature correction used to adjust the density in the model. This error can be decreased by applying a temperature correction only for those equations where temperature was substituted instead of density using the ideal gas state equation.
Table 2 shows that the quality of simulation of all precipitation-related extreme indices in INMCM5AR either improved by 3–21 % compared to INMCM5 or remained unchanged. Figures 2d, 3d show the spatial distribution of the deviations for max 1 day (RX1day) and 5 day (RX5day) precipitation according to INMCM5AR compared to INMCM5. The model with air resistance acting on falling precipitation particles compared to INMCM5 significantly underestimates RX1day and RX5day in South Africa, South and East Asia, and slightly underestimates the indicated extreme indices in Tibet.

Taking into account the air resistance acting on falling precipitation particles significantly reduces the overestimation of RX1day and RX5day observed in INMCM5 in South Africa, South and East Asia, and leads to an improvement in the quality of extreme indices associated with the precipitation amount on very rainy days and their intensity simulation by 9–21 %. At the same time, a significant overestimation of the RX1day and RX5day indices in the Amazon basin and Southeast Asia, as well as their underestimation in West Africa, still remain.

5. Conclusions

To improve the results of simulations of extreme precipitation, the effect of evaporation in the upper atmosphere was studied first. Attempts to increase the evaporation rate led to a redistribution of precipitation over an area where the model extreme precipitation intensity was already too high compared to the ERA-Interim values. As a result, this change had a negative impact on the quality of simulations of problematic indices and was rejected.

Thereafter the vertical mixing of air masses due to large-scale condensation and deep convection was implemented in the model. The $A_0$ and $C_{INC}$ model parameters, which are responsible for the intensity of these processes, were optimized. These changes have led to improvements in the simulation results of the precipitation related extreme indices by 2–10 % compared to the INMCM5.

Next, air resistance acting on falling precipitation particles was added to the model. This significantly (by 3–21 %) improved the quality of all precipitation related indices simulation results, but worsened the simulation results of some temperature indices. This degradation of the temperature indices may be due to the temperature correction which is used as a way to introduce additional density into the model.

At the same time, the above changes have not significantly improved the extreme precipitation simulation results in Southeast Asia. A peculiarity of this region is an unsatisfactory resolution of the computational grid. It is also possible that in this area the ERA-Interim reanalysis does contain significant deviations from the observational data. These issues require additional research involving, possibly, data from other reanalyses, more detailed observations, and a more detailed analysis of the hydrological cycle of the model.

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References

[1] Flato G, Marotzke J, Abiodun B et al 2014 Evaluation of climate models Climate Change 2013. The physical Science Basis (Cambridge University press) p 1535

[2] Sillmann J, Kharin V V, Zhang X et al 2013 Climate extremes indices in the CMIP5 multimodel ensemble: Part 1. Model evaluation in the present climate J. Geophys. Res. Atmospheres 118 1716–33

[3] Volodin E M, Dianskii N A and Gusev A V 2010 Simulating present-day climate with the INMCM4.0 coupled model of the atmospheric and oceanic general circulations Izv. Atmos. Ocean. Phys. 46 414–31

[4] Volodin E M, Mortikov E V, Kostrykin S V et al 2017 Simulation of the present day climate
with the new version of INM RAS climate model (in Russian) *Izv. Atmos. Ocean. Phys.* **53** 164–78

[5] Volodin E M, Mortikov E V, Kostrykin S V *et al.* 2017 Simulation of the present day climate with the climate model INMCM5 *Clim. Dyn.* **49** 3715–34

[6] Dee D P *et al.* 2011 The ERA-Interim reanalysis: Configuration and performance of the data assimilation system *Quart. Journal. Roy. Meteorol. Soc* **137** 553–97

[7] Volodin E M and Tarasevich M A 2018 Simulation of climate and weather extreme indices with the INM-CM5 climate model *Russ. Meteorol. Hydrol.* **43** 756–62

[8] Volodin E 2017 Representation of heat, moisture and momentum fluxes in climate models. Convection and condensation (In Russian) *Fund. and Appl. Climatol.* **2** 26–41