14.5 How Should a Numerical Weather Prediction (NWP) Model Forecast be made: Full Field or Anomaly?

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Basic idea

- Any variable can be decomposed into a long-term average (“climate”) and a departure (“anomaly”)
- Climate (known) can be pre-calculated using historical data such as reanalysis and doesn’t need to be predicted, only anomalies need to be predicted
- Therefore, if a model only predicts anomalies but not climate part, total forecast error might be dramatically reduced given erroneous “model climate”

Variables decomposition (Qian, Du and Ai, 2021, *BAMS*)
"anomaly = total field – climate"

$$u'(\lambda,\varphi,z,t) = u(\lambda,\varphi,z,t) - \tilde{u}(\lambda,\varphi,z,t)$$

$$v'(\lambda,\varphi,z,t) = v(\lambda,\varphi,z,t) - \tilde{v}(\lambda,\varphi,z,t)$$

$$w'(\lambda,\varphi,z,t) = w(\lambda,\varphi,z,t) - \widetilde{w}(\lambda,\varphi,z,t)$$

$$\pi'(\lambda,\varphi,z,t) = \pi(\lambda,\varphi,z,t) - \tilde{\pi}(\lambda,\varphi,z,t)$$

$$\theta'(\lambda,\varphi,z,t) = \theta(\lambda,\varphi,z,t) - \tilde{\theta}(\lambda,\varphi,z,t)$$

$$T'(\lambda,\varphi,z,t) = T(\lambda,\varphi,z,t) - \tilde{T}(\lambda,\varphi,z,t)$$

$$q'(\lambda,\varphi,z,t) = q(\lambda,\varphi,z,t) - \tilde{q}(\lambda,\varphi,z,t)$$

Anomaly form of atmospheric governing equations (Qian and Du 2022, *Meteor.*)

$$\frac{du'}{dt}=\frac{\partial u'}{\partial t}+\frac{u}{a\cos\varphi}\frac{\partial u'}{\partial\lambda}+\frac{v}{a}\frac{\partial u'}{\partial\varphi}+w\frac{\partial u'}{\partial z}=\frac{\partial u'}{\partial t}+\frac{\tilde{u}+u'}{a\cos\varphi}\frac{\partial u'}{\partial\lambda}+\frac{\tilde{v}+v'}{a}\frac{\partial u'}{\partial\varphi}+(\widetilde{w}+w')\frac{\partial u'}{\partial z}$$
$$=-\frac{C_P\theta'}{a\cos\phi}\frac{\partial\pi'}{\partial\lambda}-\frac{C_P\tilde{\theta}}{a\cos\phi}\frac{\partial\pi'}{\partial\lambda}-\frac{C_P\theta'}{a\cos\phi}\frac{\partial\tilde{\pi}}{\partial\lambda}-\frac{u'}{a\cos\varphi}\frac{\partial\tilde{u}}{\partial\lambda}-v'\frac{\partial\tilde{u}}{a\partial\varphi}-w'\frac{\partial\tilde{u}}{\partial z}+fv'+F_{u'}$$

$$\frac{dv'}{dt}=\frac{\partial v'}{\partial t}+\frac{u}{a\cos\varphi}\frac{\partial v'}{\partial\lambda}+\frac{v}{a}\frac{\partial v'}{\partial\varphi}+w\frac{\partial v'}{\partial z}=\frac{\partial v'}{\partial t}+\frac{\tilde{u}+u'}{a\cos\varphi}\frac{\partial v'}{\partial\lambda}+\frac{\tilde{v}+v'}{a}\frac{\partial v'}{\partial\varphi}+(\widetilde{w}+w')\frac{\partial v'}{\partial z}$$
$$=-\frac{C_P\theta'}{a}\frac{\partial\pi'}{\partial\varphi}-\frac{C_P\tilde{\theta}}{a}\frac{\partial\pi'}{\partial\varphi}-\frac{C_P\theta'}{a}\frac{\partial\tilde{\pi}}{\partial\varphi}-\frac{u'}{a\cos\varphi}\frac{\partial\tilde{v}}{\partial\lambda}-v'\frac{\partial\tilde{v}}{a\partial\varphi}-w'\frac{\partial\check{v}}{\partial z}-fu'+F_{v'}$$

$$\frac{dw'}{dt}=\frac{\partial w'}{\partial t}+\frac{u}{a\cos\varphi}\frac{\partial w'}{\partial\lambda}+\frac{v}{a}\frac{\partial w'}{\partial\varphi}+w\frac{\partial w'}{\partial z}=\frac{\partial w'}{\partial t}+\frac{\tilde{u}+u'}{a\cos\varphi}\frac{\partial w'}{\partial\lambda}+\frac{\tilde{v}+v'}{a}\frac{\partial w'}{\partial\varphi}+(\widetilde{w}+w')\frac{\partial w'}{\partial z}$$
$$=-C_P\theta'\frac{\partial\pi'}{\partial z}-C_P\tilde{\theta}\frac{\partial\pi'}{\partial z}-C_P\theta'\frac{\partial\tilde{\pi}}{\partial z}-\frac{u'}{a\cos\varphi}\frac{\partial\widetilde{w}}{\partial\lambda}-v'\frac{\partial\widetilde{w}}{a\partial\varphi}-w'\frac{\partial\breve{w}}{\partial z}+F_{w'}$$

$$\frac{d\pi'}{dt}=\frac{\partial\pi'}{\partial t}+\frac{u}{a\cos\varphi}\frac{\partial\pi'}{\partial\lambda}+\frac{v}{a}\frac{\partial\pi'}{\partial\varphi}+w\frac{\partial\pi'}{\partial z}=\frac{\partial\pi'}{\partial t}+\frac{\tilde{u}+u'}{a\cos\varphi}\frac{\partial\pi'}{\partial\lambda}+\frac{\tilde{v}+v'}{a}\frac{\partial\pi'}{\partial\varphi}$$
$$=-\frac{1}{(\gamma-1)}\pi'\cdot D_3'-\frac{1}{(\gamma-1)}\tilde{\pi}\cdot D_3'-\frac{1}{(\gamma-1)}\pi'\cdot\widetilde{D}_3+\frac{1}{(\gamma-1)}\frac{F_{\tilde{\theta}}}{\tilde{\theta}+\theta'}-\frac{1}{(\gamma-1)}\frac{F_{\tilde{\theta}}}{\tilde{\theta}}+\frac{1}{(\gamma-1)}\frac{F_{\theta'}}{\tilde{\theta}+\theta'}$$
$$-\frac{u'}{a\cos\varphi}\frac{\partial\tilde{\pi}}{\partial\lambda}-v'\frac{\partial\tilde{\pi}}{a\partial\varphi}-w'\frac{\partial\check{\pi}}{\partial z}$$

$$\frac{d\theta'}{dt}=\frac{\partial\theta'}{\partial t}+\frac{u}{a\cos\varphi}\frac{\partial\theta'}{\partial\lambda}+\frac{v}{a}\frac{\partial\theta'}{\partial\varphi}+w\frac{\partial\theta'}{\partial z}=\frac{\partial\theta'}{\partial t}+\frac{\tilde{u}+u'}{a\cos\varphi}\frac{\partial\theta'}{\partial\lambda}+\frac{\tilde{v}+v'}{a}\frac{\partial\theta'}{\partial\varphi}+(\widetilde{w}+w')\frac{\partial\theta'}{\partial z}$$
$$=\frac{F_{\tilde{\theta}}}{\tilde{\pi}+\pi'}-\frac{F_{\tilde{\theta}}}{\tilde{\pi}}+\frac{F_{\theta'}}{\tilde{\pi}+\pi'}-\frac{u'}{a\cos\varphi}\frac{\partial\tilde{\theta}}{\partial\lambda}-v'\frac{\partial\tilde{\theta}}{a\partial\varphi}-w'\frac{\partial\tilde{\theta}}{\partial z}$$

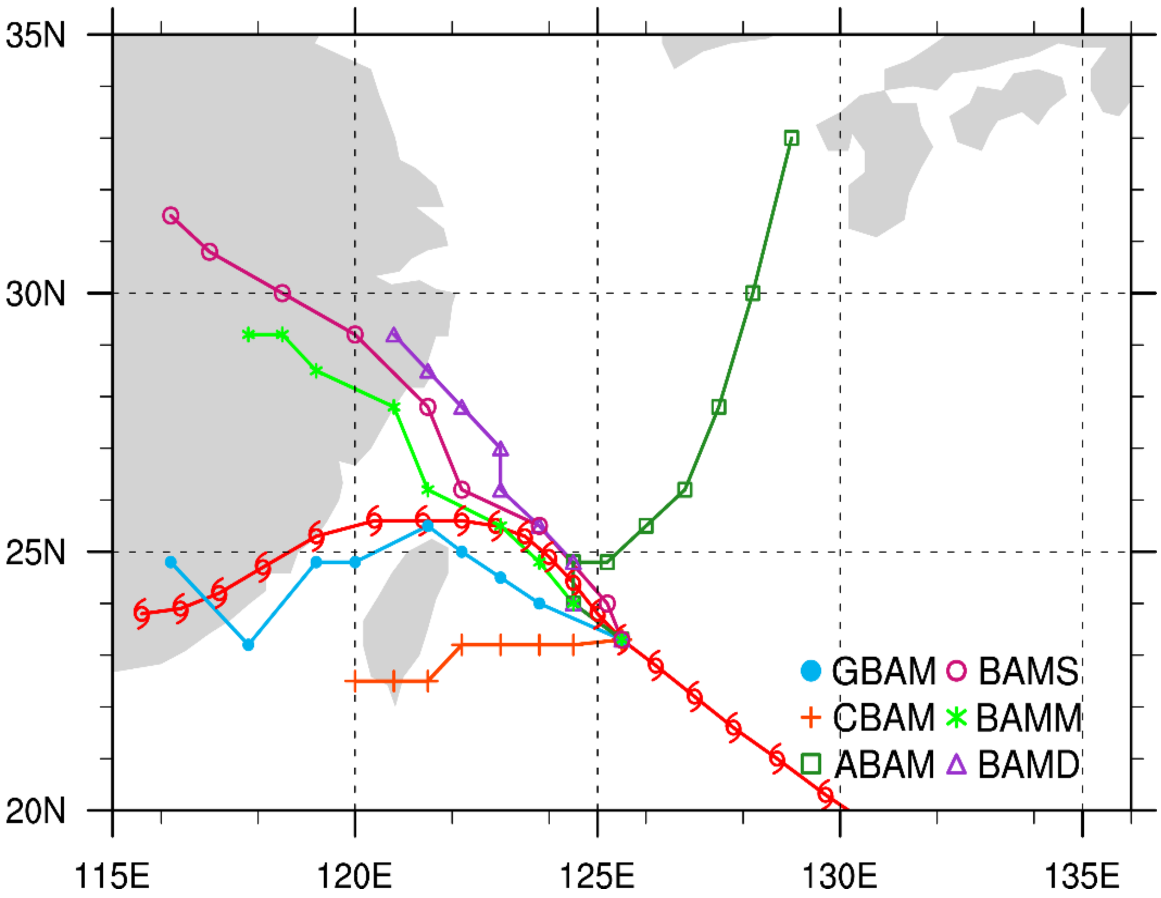
$$T'=\pi'\theta'+\tilde{\pi}\theta'+\pi'\tilde{\theta}$$

$$\frac{\partial q'}{\partial t}=-\left[u'\frac{\partial q'}{\partial x}+v'\frac{\partial q'}{\partial y}+w'\frac{\partial q'}{\partial z}\right]-\left[u'\frac{\partial\tilde{q}}{\partial x}+v'\frac{\partial\tilde{q}}{\partial y}+w'\frac{\partial\tilde{q}}{\partial z}\right]-\left[\tilde{u}\frac{\partial q'}{\partial x}+\tilde{v}\frac{\partial q'}{\partial y}+\widetilde{w}\frac{\partial q'}{\partial z}\right]+Q'_{source}-Q'_{sink}$$

The 48h track forecasts of Typhoon Aere, initiated at 0600 UTC 23 August 2004

$$\frac{\partial \varsigma}{\partial t} = -u\frac{\partial \varsigma}{\partial x} - v\frac{\partial \varsigma}{\partial y} - \beta v \qquad \text{(full-field BAM)} \qquad (1)$$

$$\frac{\partial \varsigma'}{\partial t} = -[(\tilde{u} + u')\frac{\partial \varsigma'}{\partial x} + (\tilde{v} + v')\frac{\partial \varsigma'}{\partial y}] - \beta v' \qquad \text{(anomaly GBAM)} \qquad (2)$$

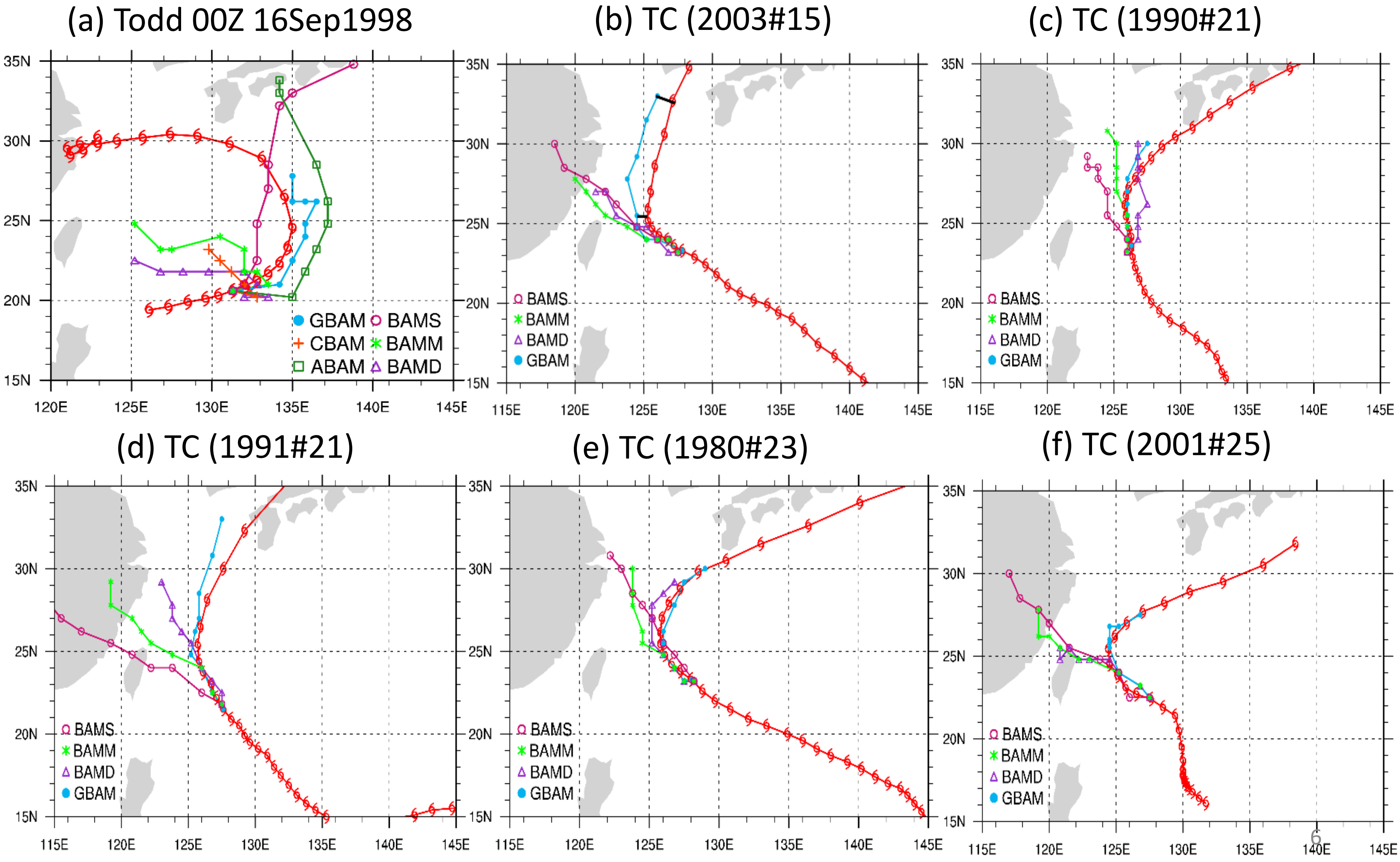


(A total of 133 TCs occurred in the Western Pacific during 1979-2011)

GBAM vs. BAM [three versions: BAMS (shallow 850–700 hPa), BAMM (medium, 850–400 hPa), and BAMD (deep, 850–200hPa)]. GBAM is applied to anomaly Max-Vor/Min-Div level

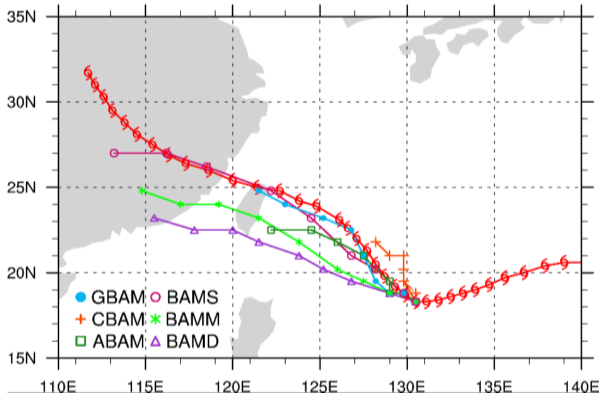
(Huang, Du, and Qian, 2015, *WAF*)

Turning tracks (48hr forecasts)

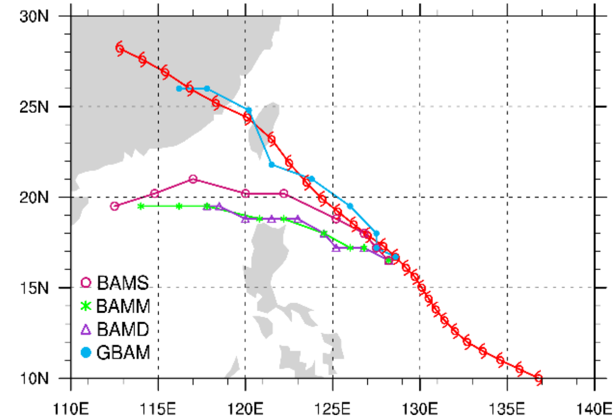


Straight tracks (48hr forecasts)

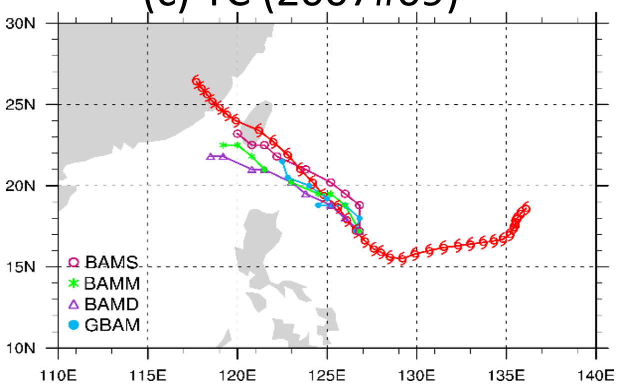
(a) Herb 18Z 28Jul 1996



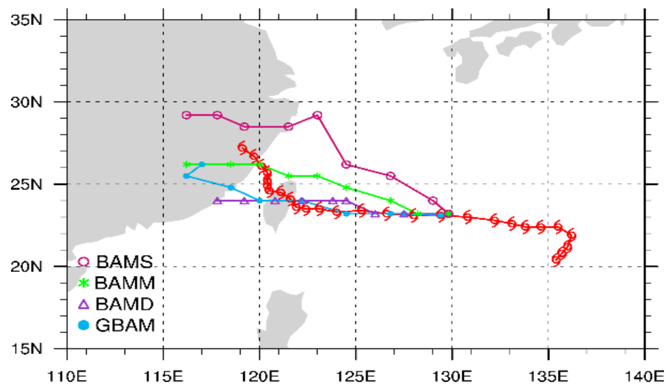
(b) TC (1994#08)



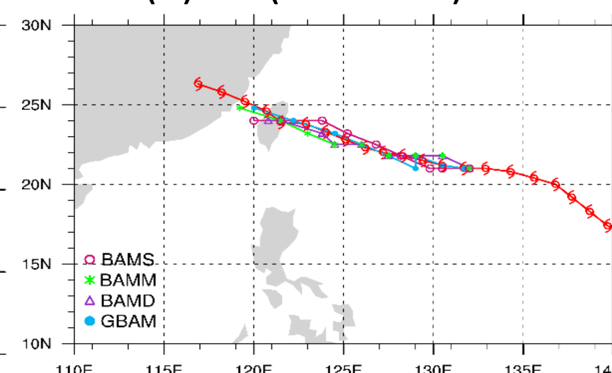
(c) TC (2007#09)



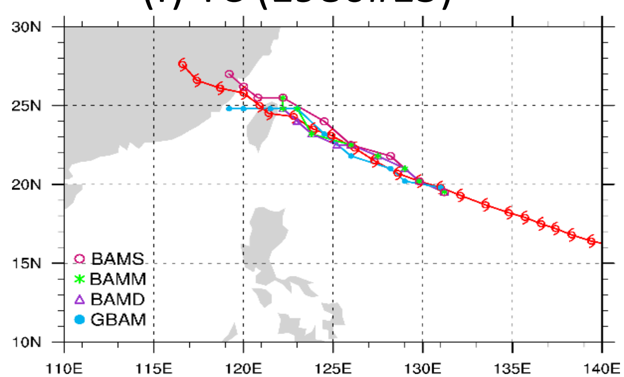
(d) TC (2009#09)



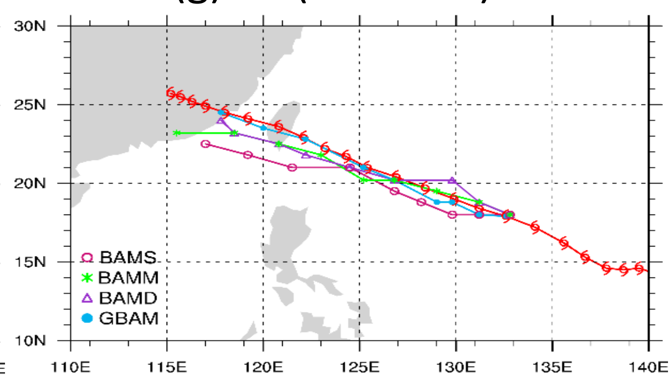
(e) TC (2005#13)



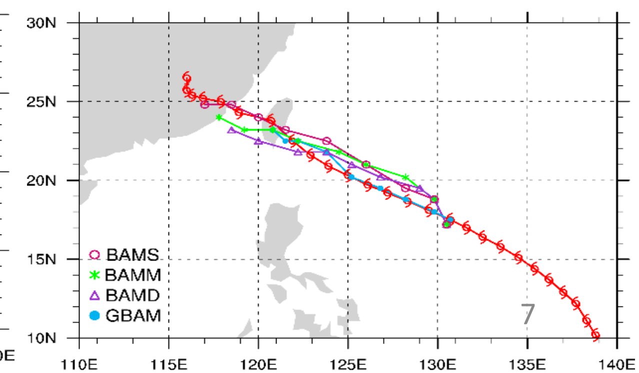
(f) TC (1980#15)



(g) TC (1990#17)



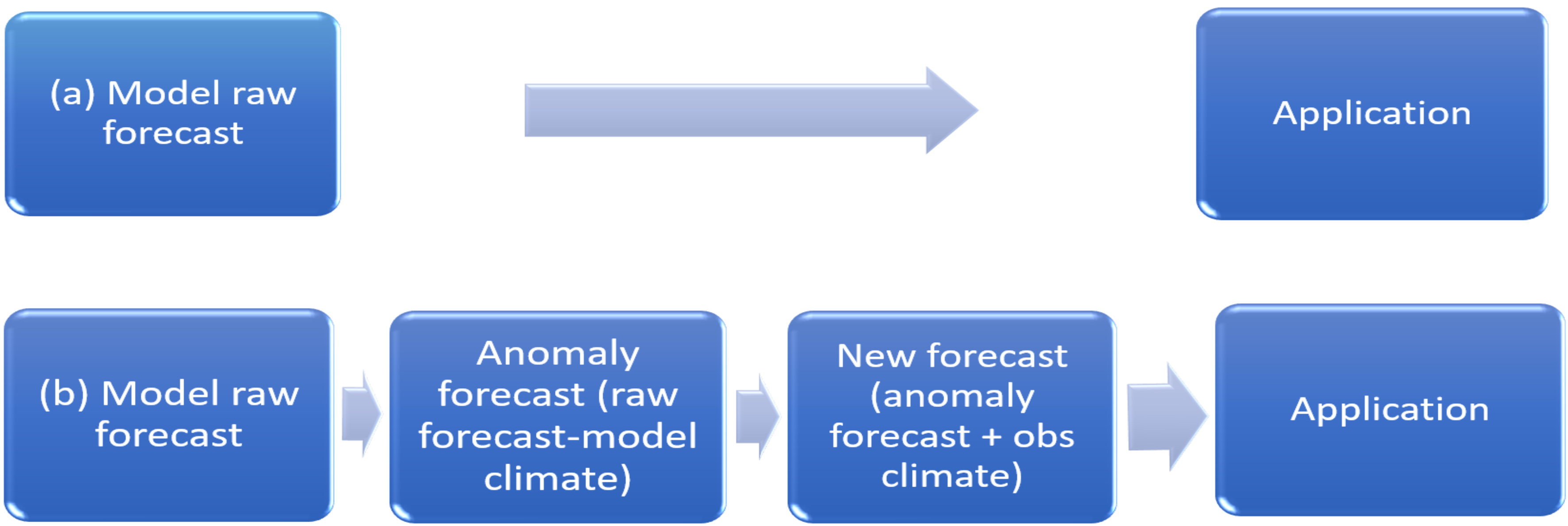
(h) TC (2000#18)



Anomaly-based post-processing (model climate is replaced by observed climate) (Du and Deng 2022, *Atmos.*)

$$fcst_{anomaly} = fcst_{raw} - climate_{model} \quad (1)$$

$$fcst_{new} = (fcst_{raw} - climate_{model}) + climate_{observed} \quad (2)$$



Lorenz model (Lorenz-84)

The 3-variable (X, Y, and Z) nonlinear Lorenz model (Lorenz 1984 and 1990)

$$\frac{dX}{dt} = -Y^2 - Z^2 - aX + aF$$

$$\frac{dY}{dt} = XY - bXZ - Y + G$$

$$\frac{dZ}{dt} = bXY + XZ - Z$$

X represents zonal wind, Y and Z are superposed waves, and t is time. The parameters a, b, F and G can be viewed as model physics, where a and b are drag damping, and F and G are symmetric and asymmetric thermal forcing.

Experiment design

- Perfect model → 30 years for calculating "observed climate"; the 31st year as truth for verification

$$X_0 = [2.0 + 2\cos(\frac{2\pi*day}{365})] + RAN\_x(year)$$

$$Y_0 = [1.0 + 2\cos(\frac{2\pi*day}{365})] + RAN\_y(year)$$

$$Z_0 = [0.0 + 2\cos(\frac{2\pi*day}{365})] + RAN\_z(year)$$

- Imperfect model→ 30 years for calculating "model climate"; the 31st year as forecasts for verification

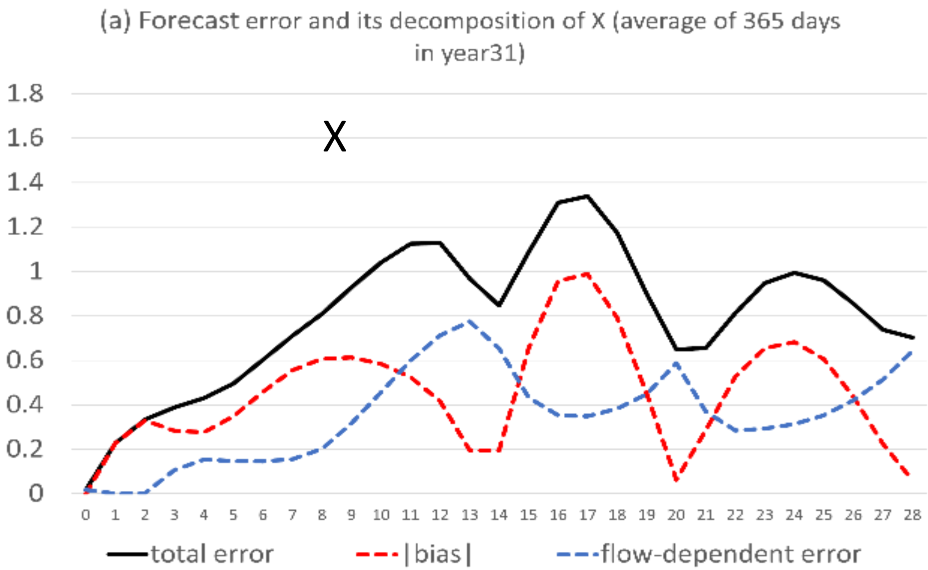
$$X'_0 = [2.0 + 2\cos\left(\frac{2\pi*day}{365}\right) + RAN_{\_x(year)}] + RAN_{\_x(day)}$$

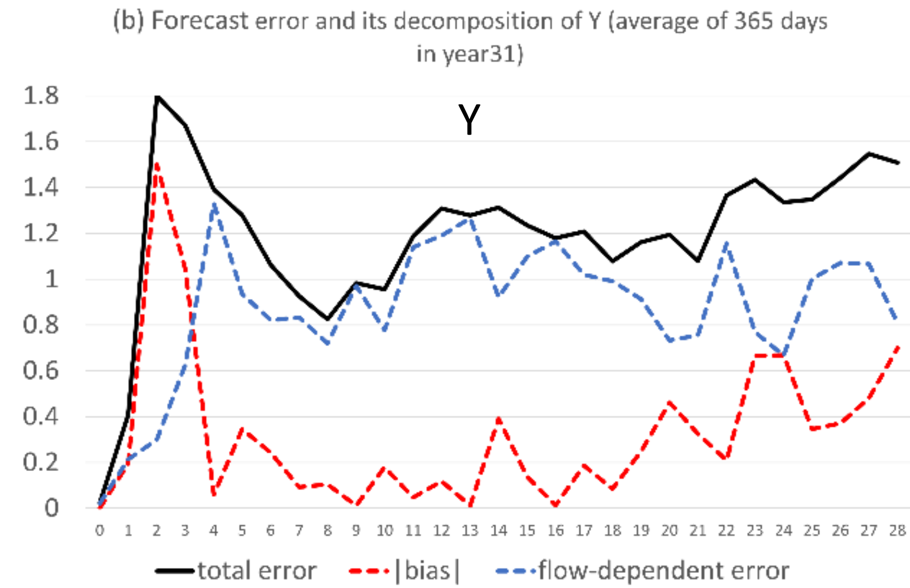
$$Y'_0 = [1.0 + 2\cos\left(\frac{2\pi*day}{365}\right) + RAN_{\_y(year)}] + RAN\_y(day)$$

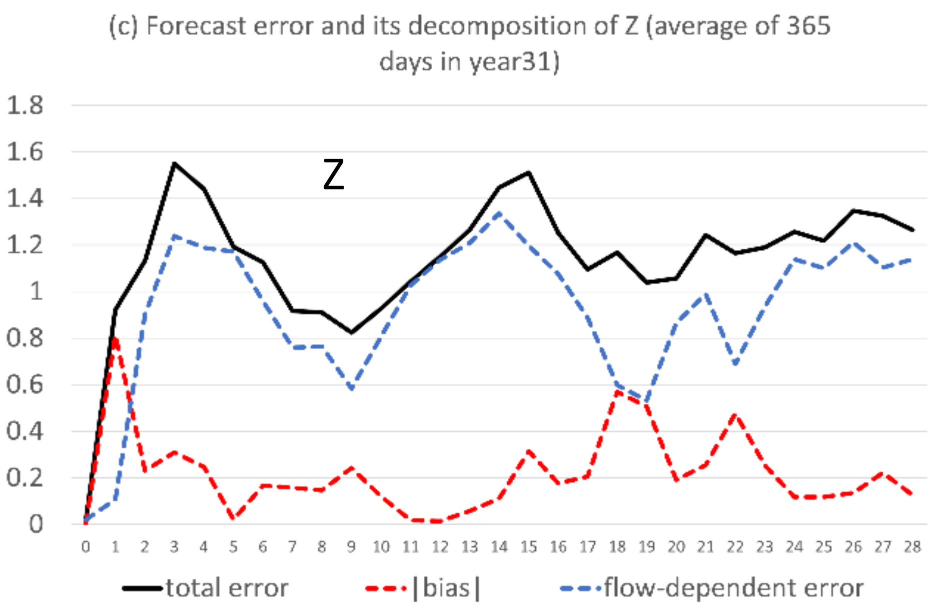
$$Z'_0 = [0.0 + 2\cos\left(\frac{2\pi*day}{365}\right) + RAN_{\_z(year)}] + RAN\_z(day)$$

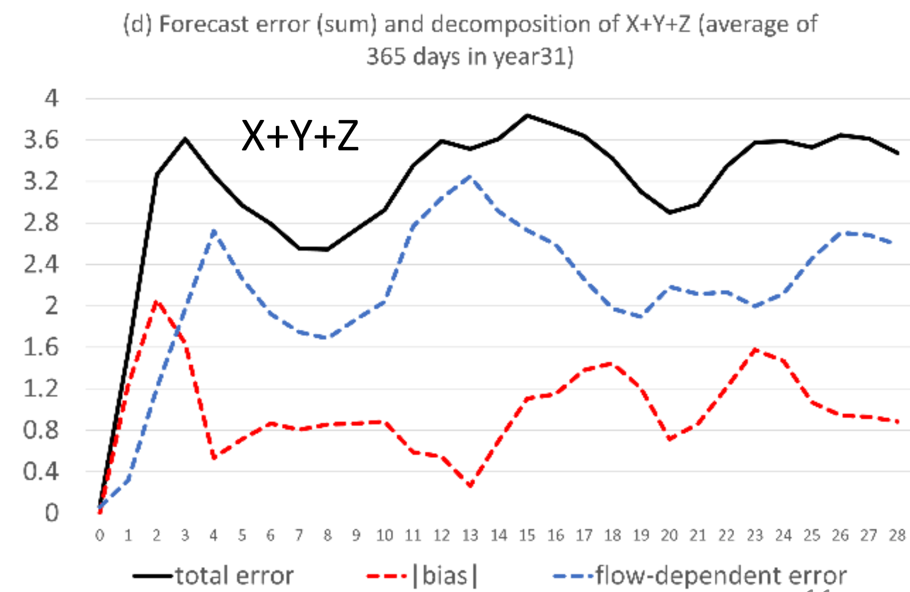
- Forecast once per day with forecast length of 1-28 days (4 weeks trying to include sub-seasonal range)

Total error and its decomposition

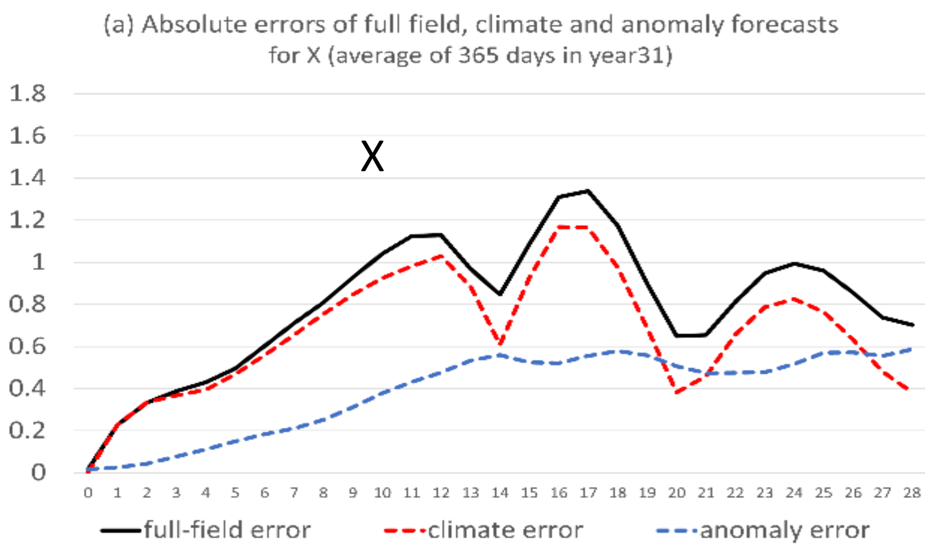


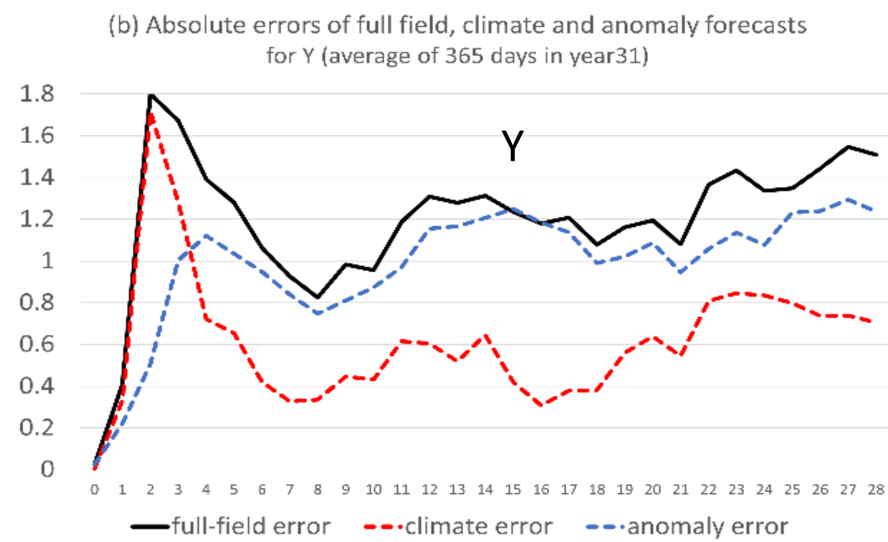


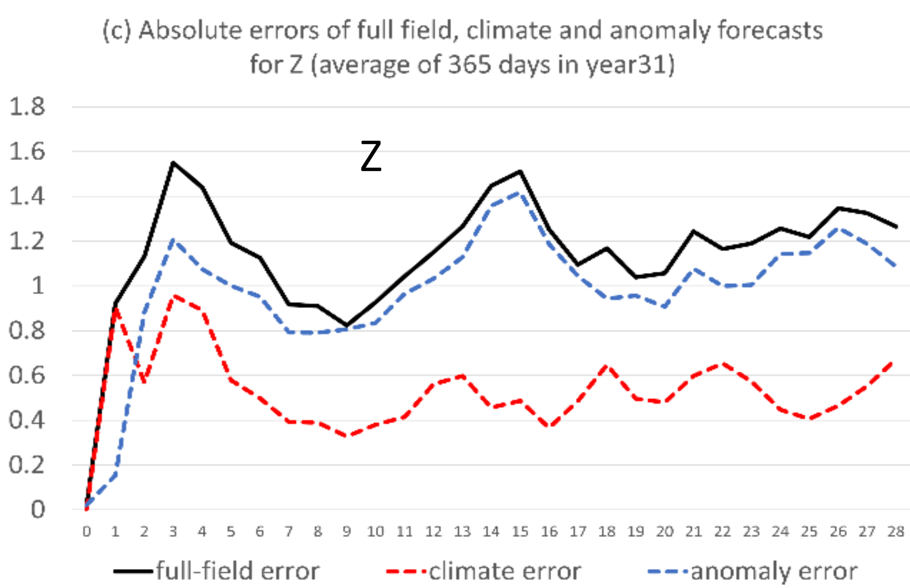


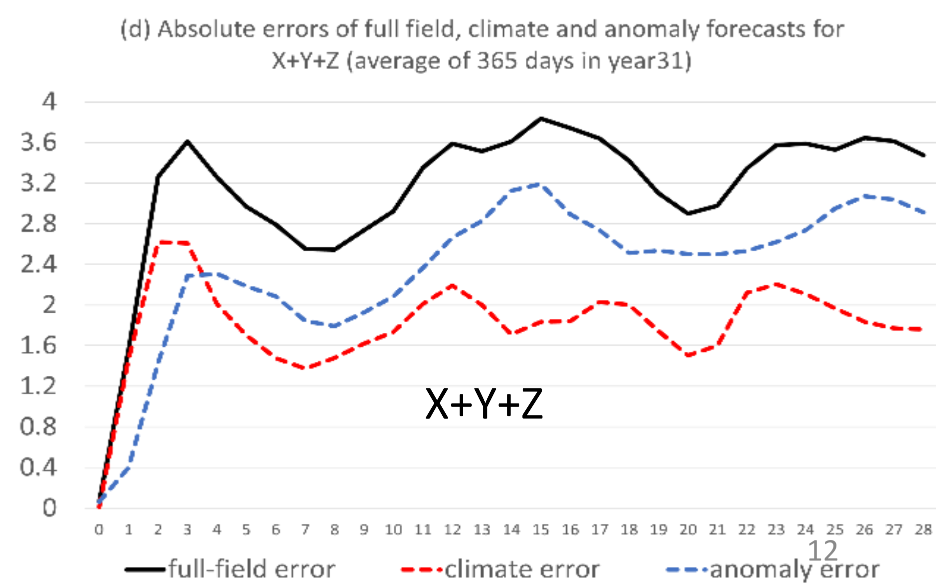


Forecast errors of the full, climate and anomaly fields





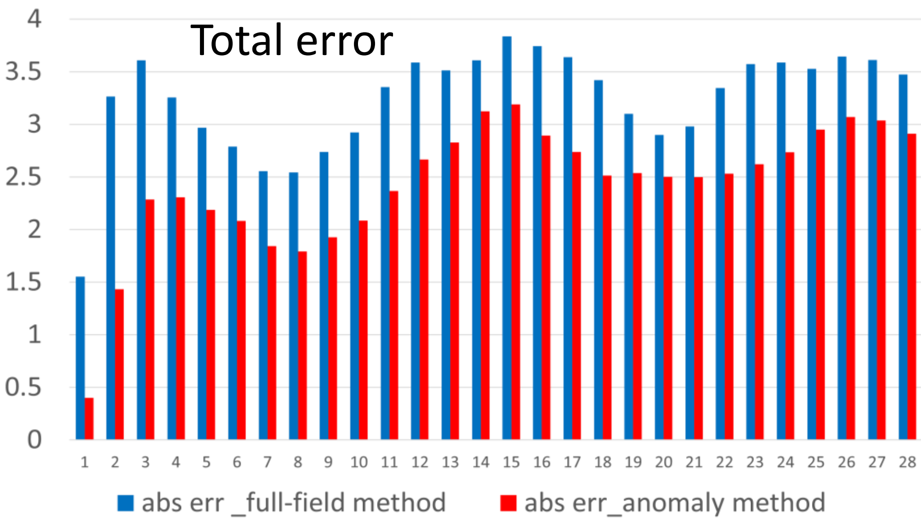




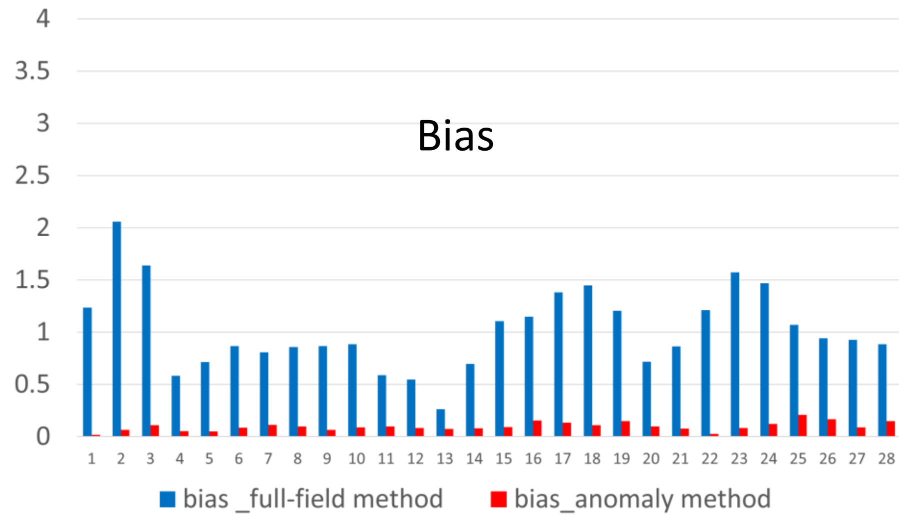
Magnitude improvement: error changes before and after

X+Y+Z average

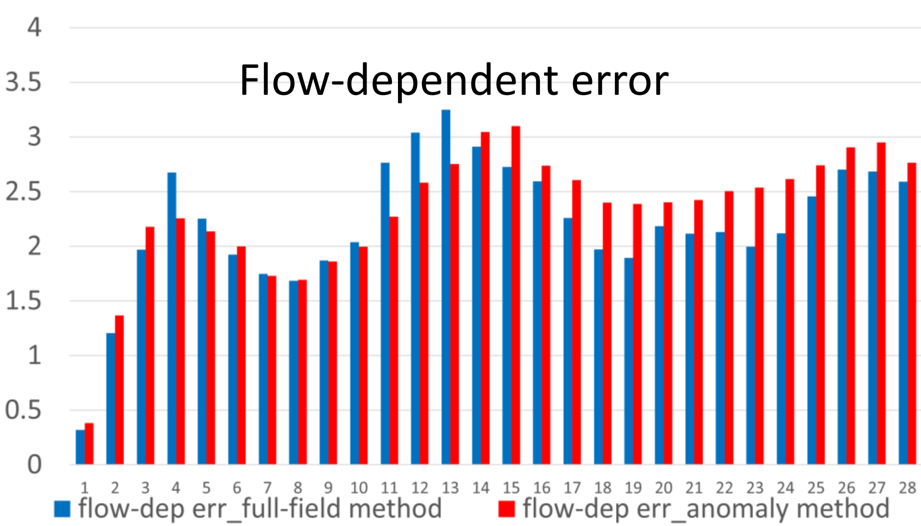
(a) Average change of absolute error for X, Y and Z (average of 365 days in year31)



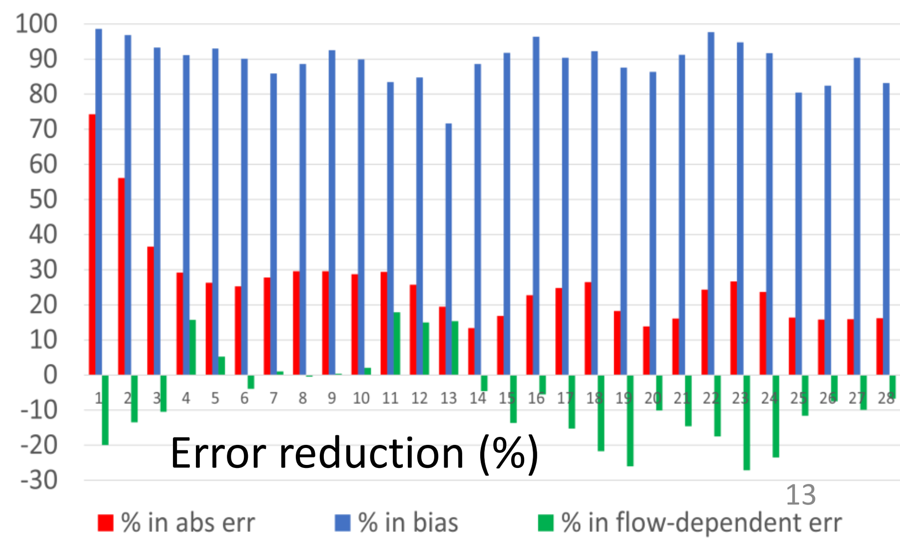
(b) Average change of bias error for X, Y and Z (average of 365 days in year31)



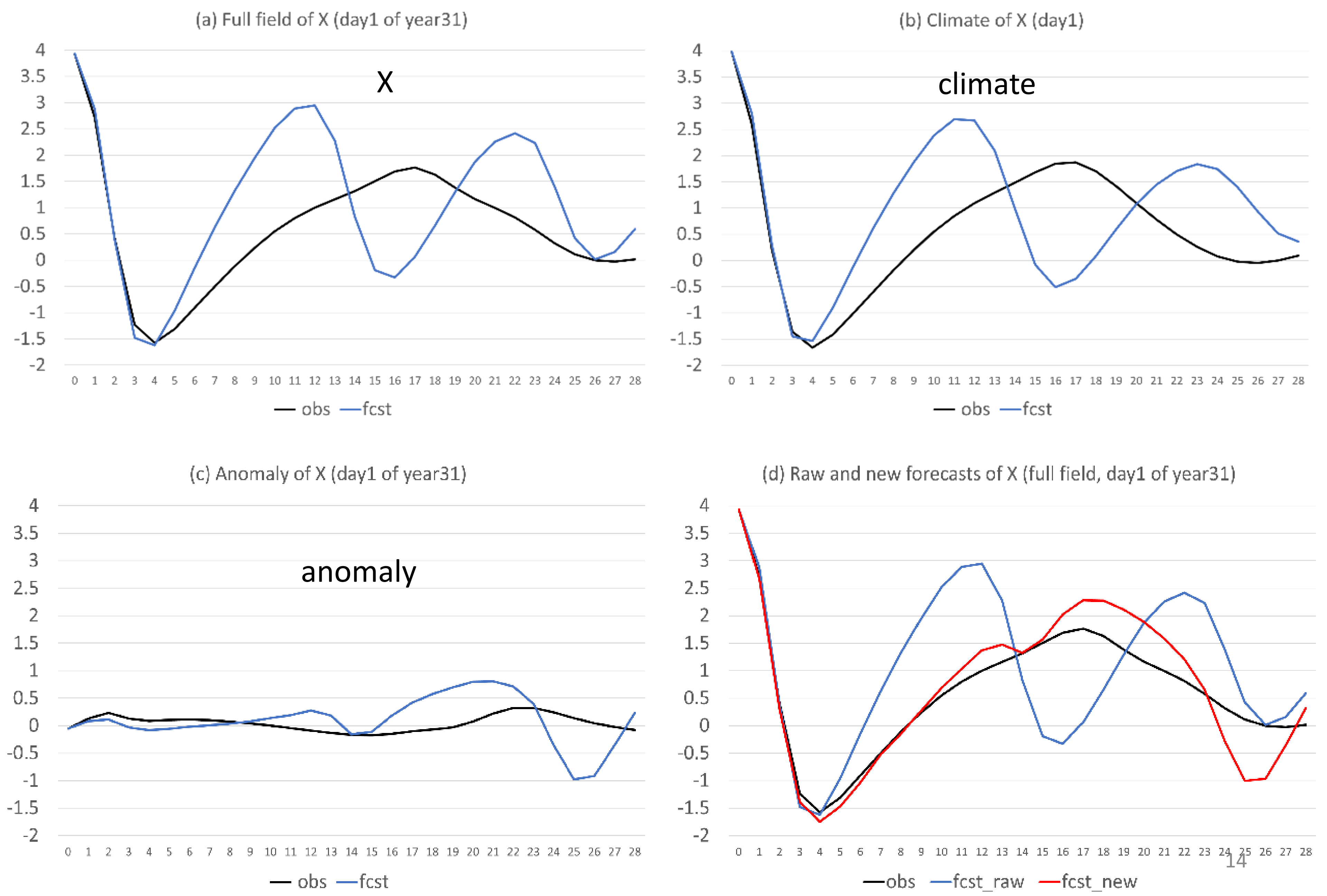
(c) Average change of flow-dependent error for X, Y and Z (average of 356 days in year31)



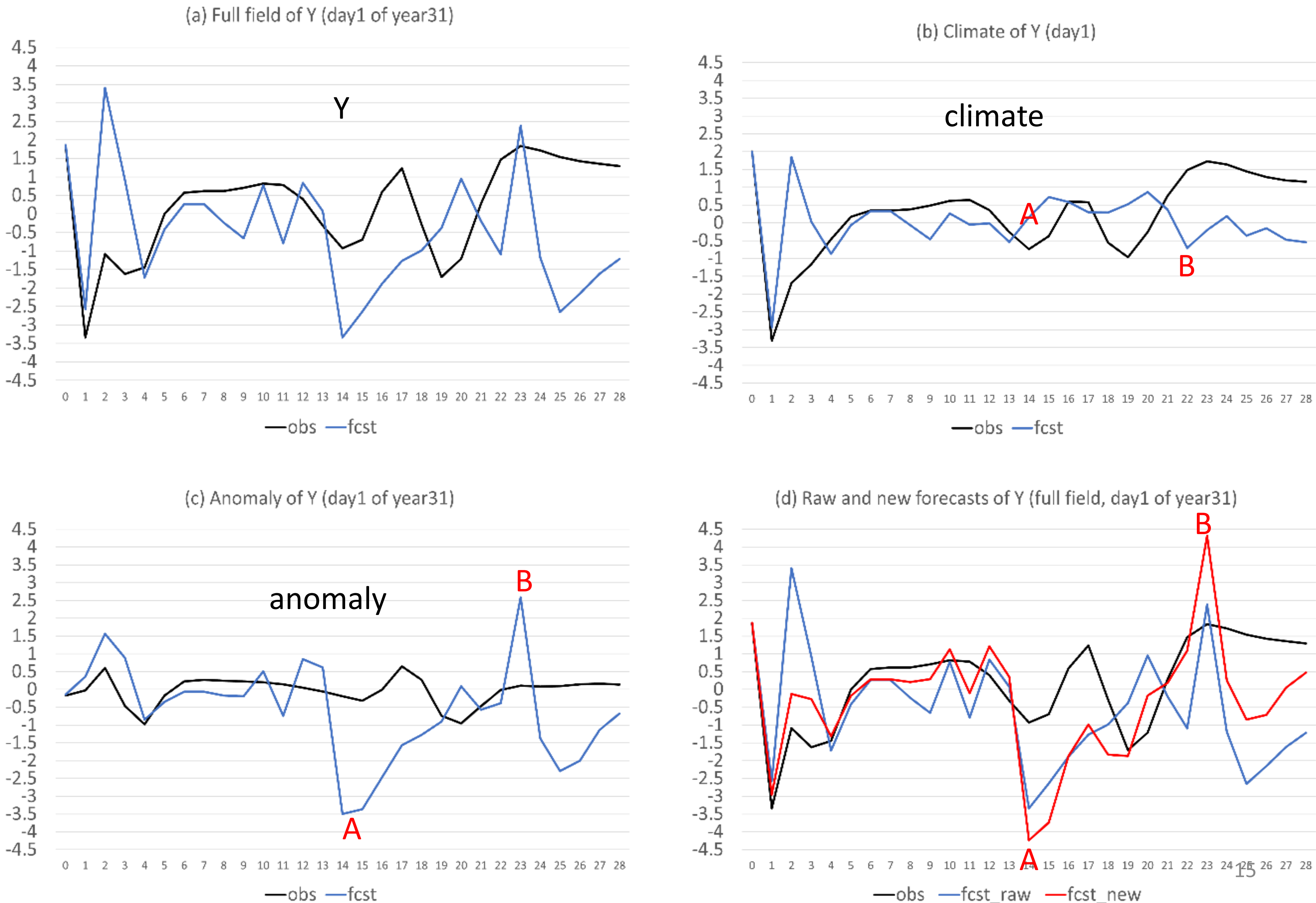
(d) Average percentage of error reduction for X, Y and Z (%) (average of 365 days in year31)



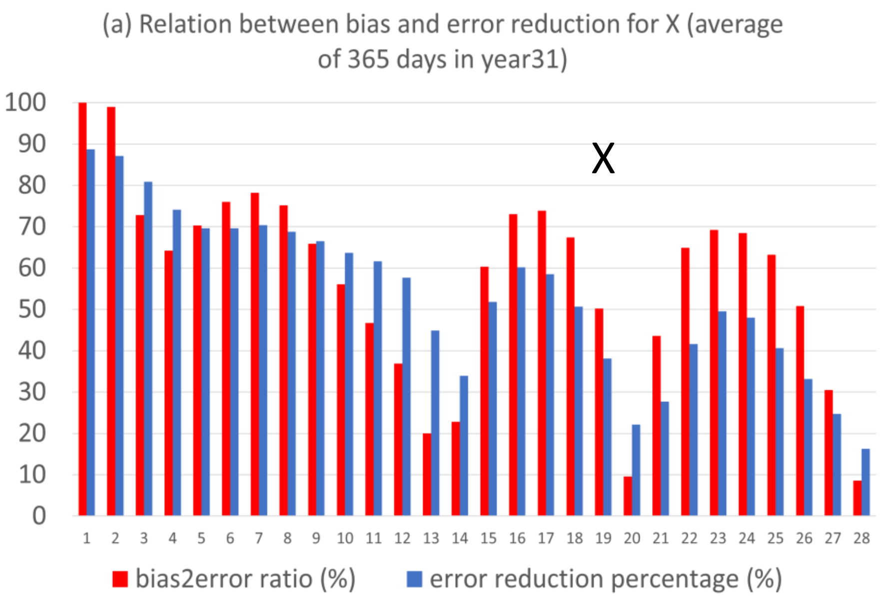
Situation 1: larger bias and smaller flow-dependent errors

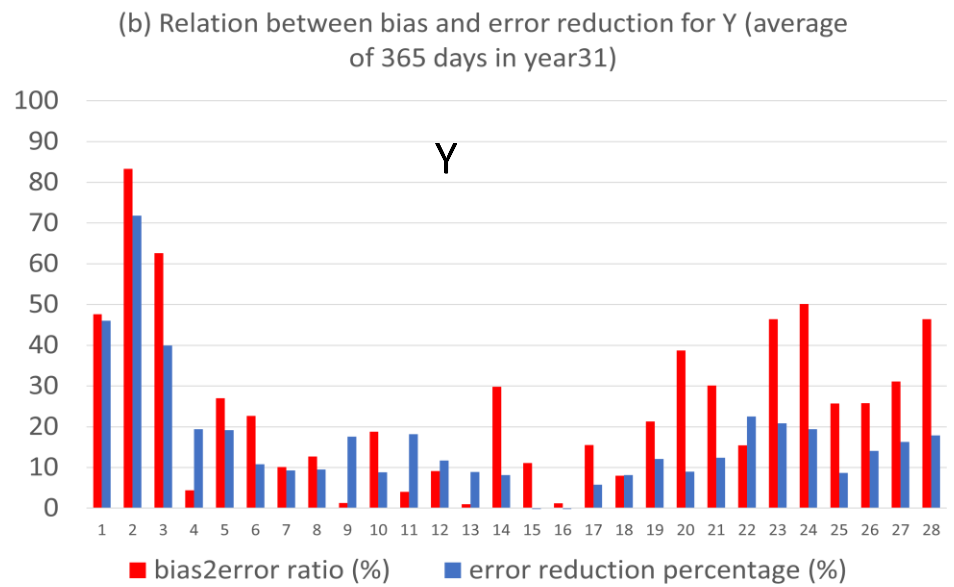


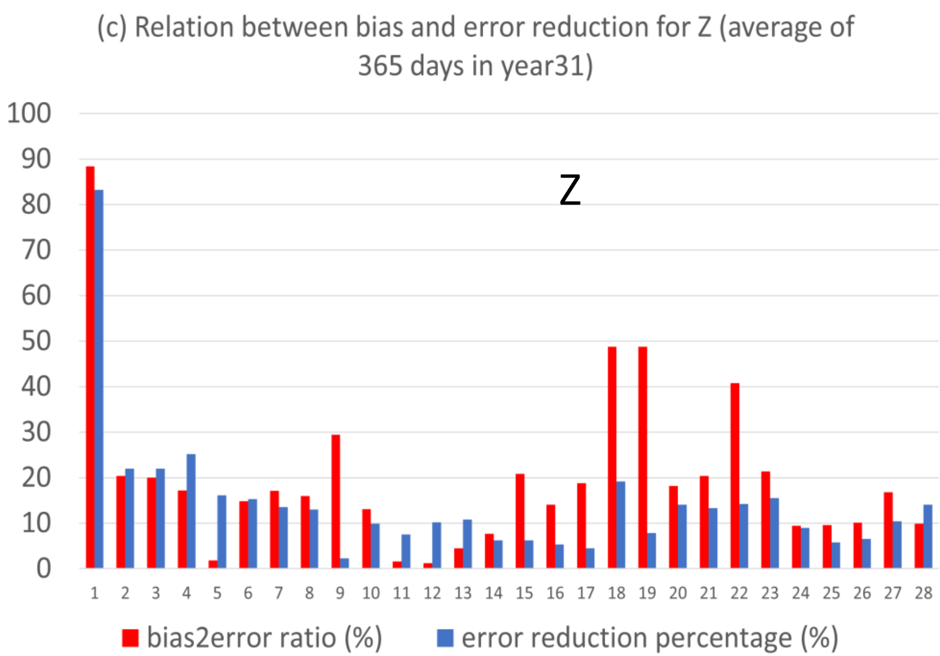
Situation 2: smaller bias error and larger flow-dependent error

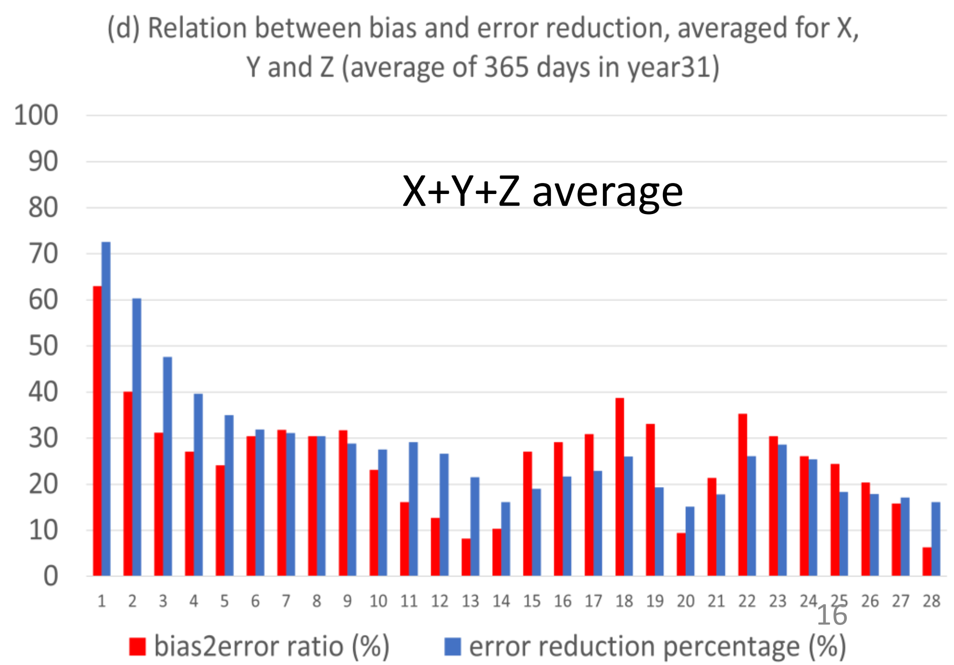


Relationship between Bias error and forecast improvement









What we learn?

- Bias error mainly stems from climate part and flow-dependent error mainly stems from anomaly part. Therefore, anomaly-based NWP model could be a systematic-error free system
- Could anomaly-based NWP model be a possible direction for the next-generation NWP? If the answer is “yes”, an NWP center needs to invest some resources on developing such a state-of-the-art anomaly-based NWP model
- High-resolution (both spatial and temporal) reanalysis and model’s reforecast datasets are needed