IDOL: Meeting Diverse Distribution Shifts with Prior Physics for Tropical Cyclone Multi-Task Estimation

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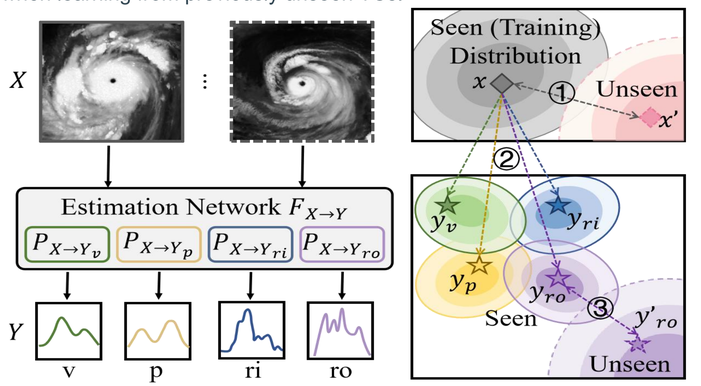
NEURAL INFORMATION PROCESSING SYSTEMS

Challenges

Generally speaking, deep learning models rely on the assumption that the training and test data are drawn from the same underlying distribution, referred to as in-distribution, to make reliable predictions. However, in real-world scenarios, the spatiotemporal heterogeneity of TC environmental fields often gives rise to complex and diverse developmental pathways, resulting in out-of-distribution (OOD) data during inference. Consequently, ignoring the inherent distribution of network embeddings, existing methods may fail to learn features that capture all possible variations in TC evolution. This, in turn, severely limits the models' ability to generalize effectively when learning from previously unseen TCs.

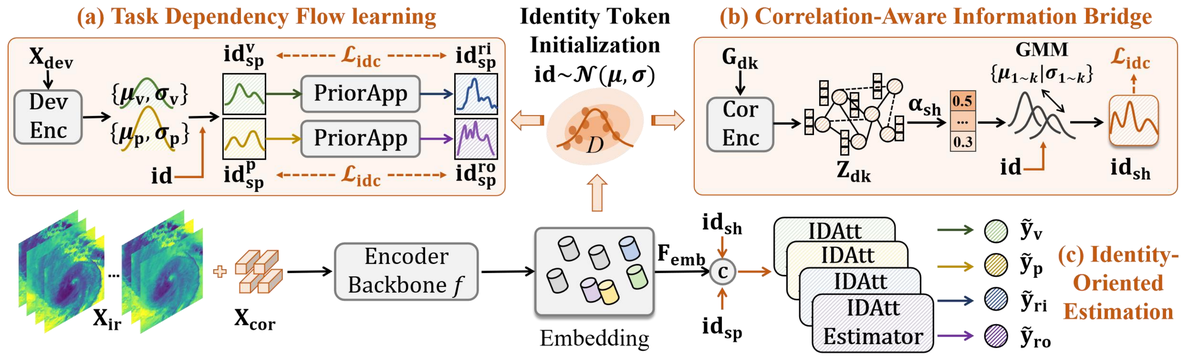


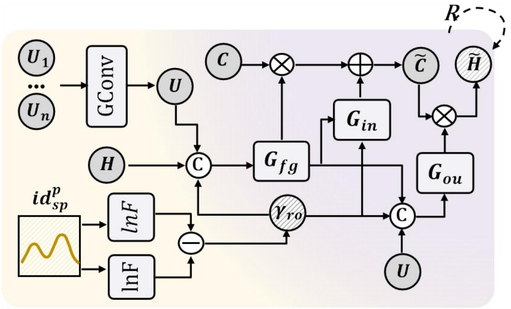
Diverse Distribution Shifts in TC Multi-Task Estimation. The v, p, ri and ro represent the wind speed, pressure, inner-core and outer-core size of TC, respectively.

Contributions

- To address concept shift in multi-task learning, we propose a Task Dependency Flow learning module. By incorporating the prior wind field model, the conditional probabilities of multiple specific tasks are decoupled to model the dependencies among tasks, thereby facilitating the learning of distinct task-specific identities.
- To address covariate and label shifts, we design a Correlation-Aware Information Bridge module. By incorporating physical correlations to regulate the latent feature distribution, the task-shared identity token is modeled to serve as an information bridge that preserves the core information of both input and output in TC estimation.
- Comprehensive experiments are conducted on multiple TC estimation and prediction tasks to evaluate the effectiveness of the proposed IDOL. The results demonstrate the efficacy of IDOL in handling diverse distribution shifts through feature space constraints informed by prior physical knowledge.

IDOL Franmework (https://github.com/Zjut-MultimediaPlus/IDOL)





The framework of the proposed PriorAP.

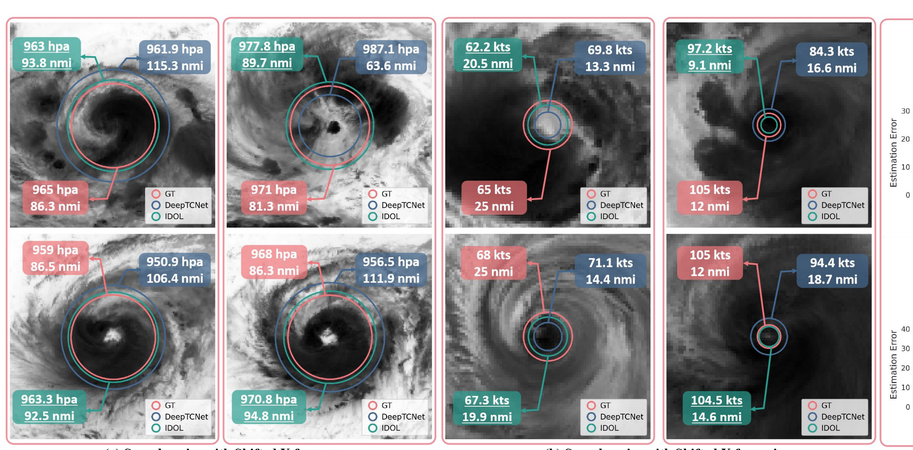
Experiments and Results

Table1. Comparison of TC multi-task estimation methods on the Physical Dynamic TC datasets.

Categories	Comparison Methods	Wind Speed MAE	Wind Speed RMSE	Wind Speed STD	Pressure MAE	Pressure RMSE	Pressure STD	Inner-Core Size MAE	Inner-Core Size RMSE	Inner-Core Size STD	Outer-Core Size MAE	Outer-Core Size RMSE	Outer-Core Size STD
Traditional	ADT	11.2	14.2	-	8	10.2	-	-	-	-	-	-	-
	MTCSWA	-	-	-	-	-	-	11.7	18.2	-	26.4	33	-
Multi-Modal Fusion	STIA	10.7	14.41	9.67	-	-	-	-	-	-	-	-	-
	NS	-	-	-	-	-	-	10.5	15.51	11.44	26.35	36.12	24.71
	TC-MTLNet	13.82	18.06	11.62	12	15.46	9.79	-	-	-	31.49	42.83	29.14
	DeepTCNet	8.84	11.76	7.76	8.13	10.42	5.31	8.09	13.71	11.25	25.86	33.49	21.29
	PeRCNN	10.04	13.23	8.61	6.99	8.78	6.52	8.56	14.13	11.25	24.97	32.94	21.48
Invariant Learning	IRM	9.54	12.93	8.71	7.71	10.06	6.47	8.12	13.7	11.06	25.6	34.7	23.37
	V-Rex	10	13.29	8.76	8.13	10.48	6.6	8.21	13.7	10.94	25.4	34	22.59
	SADE	10.01	13.47	8.66	8.09	10.55	6.76	8.23	13.41	10.59	25.95	34.19	22.26
	DirMixE	9.93	13.27	8.8	7.92	10.27	6.54	8.47	14.2	11.37	25.5	34.3	23.02
	IDOL	**5.93**	**7.6**	**4.75**	**5.77**	**7.15**	**4.23**	**6.24**	**12.06**	**10.31**	**17.06**	**23.26**	**15.8**

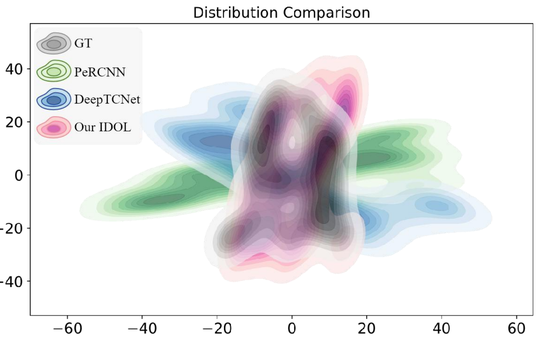
Table2. Ablation Study

Net_f	id_{sp}	id_{sh}	Wind Speed MAE	Wind Speed RMSE	Wind Speed STD	Pressure MAE	Pressure RMSE	Pressure STD	Inner-Core Size MAE	Inner-Core Size RMSE	Inner-Core Size STD	Outer-Core Size MAE	Outer-Core Size RMSE	Outer-Core Size STD
✓			10.13	13.25	8.54	7.79	10.13	6.47	8.32	13.87	11.1	28.58	37.66	24.52
✓	✓		7.24	9.13	5.55	6.66	8.27	4.97	7.37	13.24	10.99	24.91	33.28	22.07
✓	✓	✓	**5.93**	**7.6**	**4.75**	**5.77**	**7.15**	**4.23**	**6.24**	**12.06**	**10.31**	**17.06**	**23.26**	**15.8**

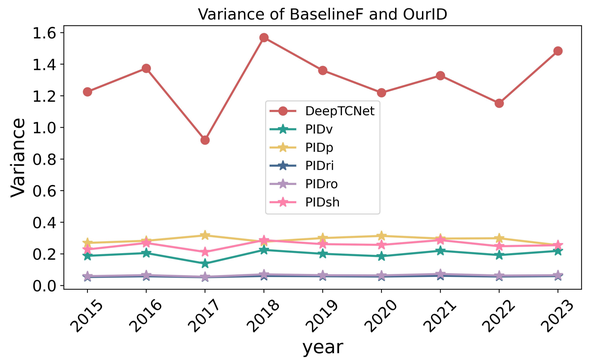


(a) Sample pairs with Shifted X for p-ro (b) Sample pairs with Shifted X for v-ri

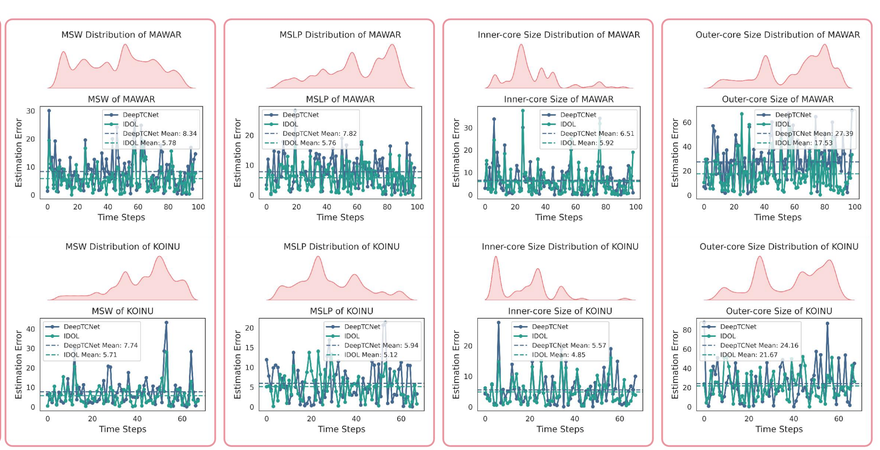
Estimation performance under covariate shift for (a) pressure and outer-core size (p-ro) and (b) wind speed and inner-core size (v-ri).



Distribution visualization of test set estimation results based on KDE.



Variance comparison between physical identity (PID) tokens and the features extracted by DeepTCNet.



Estimation performance under label shift and concept shift.
Each vertical red box indicates a pair of samples exhibiting distribution shift.